EXHIBITS 1-5 REDACTED IN THEIR ENTIRETY

EXHIBIT 6

IN THE UNITED STATES DISTRICT COURT
FOR THE DISTRICT OF DELAWARE

VOLTERRA SEMICONDUCTOR LLC, Plaintiff, v. MONOLITHIC POWER SYSTEMS, INC., Defendant.	C.A. No. 19-2240-CFC **CONTAINS RESTRICTED - ATTORNEYS' EYES ONLY INFORMATION**

PLAINTIFF'S SECOND SUPPLEMENTAL OBJECTIONS AND RESPONSES TO DEFENDANT'S FIRST SET OF INTERROGATORIES TO PLAINTIFF (NOS. 1–6)

Pursuant to Rules 26 and 33 of the Federal Rules of Civil Procedure, Plaintiff Volterra Semiconductor LLC ("Volterra") hereby serves their Second Supplemental Objections and Responses to Defendant Monolithic Power Systems, Inc. ("Monolithic")'s First Set of Interrogatories (Nos. 1-6).

GENERAL OBJECTIONS

1. Volterra objects to the Interrogatories, "Instructions," and "Definitions," to the extent that they are inconsistent with, enlarge upon, or exceed the scope of discovery authorized by the Federal Rules of Civil Procedure, the Local Rules of the District of Delaware, any applicable Court Order, or any stipulation or agreement between the parties. Volterra will abide by the Federal Rules of Civil Procedure, the Local Rules of the United States District Court for the District of Delaware, any applicable Court Order, and any stipulation or agreement between the parties in responding to Monolithic's Interrogatories.

2. By identifying a document in response to an Interrogatory, Volterra does not admit that the document is free of information that is privileged or immune from discovery, nor does Volterra waive its right to withhold any portion of the document that is privileged or immune from discovery.

3. By identifying a document in response to an Interrogatory, Volterra does not admit that the document is relevant or admissible at a hearing or trial in this action (e.g., as coming within an exception to the hearsay rule, Fed. R. Evid. 802).

4. In those instances where the response to an Interrogatory can be derived from Volterra's business records—or from an examination, audit or inspection of such business records— and the burden of deriving or ascertaining the answer is substantially the same for Monolithic as it is for Volterra, Volterra may specify the record from which a complete answer may be ascertained and afford Monolithic a reasonable opportunity to audit, inspect, and copy such records, or may provide copies of such records in accordance with Federal Rule of Civil Procedure 33(d).

5. Volterra objects to the Interrogatories to the extent that they seek information protected by the attorney-client privilege, work product doctrine, common interest privilege, and/or any other applicable privilege or immunity.

6. Volterra objects to the Interrogatories to the extent that they seek to obtain names of persons, names of third-party products, codes, and other information not within Volterra's possession, custody, or control.

7. Volterra objects to the Interrogatories on the ground and to the extent that they seek information already in Monolithic's possession, information that is a matter of public record or information that is otherwise equally available to Monolithic.

8. Volterra objects to each Interrogatory to the extent that it seeks information which is confidential or proprietary to, or the trade secrets of, a non-party, and which Volterra is under an obligation and duty to the non-party to not disclose, unless the non-party agrees to a suitable protective order or consents in writing to disclosure to Monolithic.

9. Volterra objects to the Interrogatories to the extent that they contain discrete subparts. Each subpart should count as a separate interrogatory toward the limit on interrogatories imposed by the Federal Rules of Civil Procedure and the Scheduling Order.

10. Volterra objects to the Interrogatories to the extent that they are vague, ambiguous, indefinite, overbroad, unduly burdensome, duplicative, cumulative, unlimited in time or scope, or otherwise unclear as to the information sought. Volterra will make every effort to construe the Interrogatories in good faith consistent with its obligations under the Federal Rules of Civil Procedure and applicable Local Rules.

11. Volterra objects to the Interrogatories on the ground and to the extent that they seek information not relevant to any claim or defense in this litigation, and are not reasonably calculated to lead to the discovery of admissible evidence.

12. Volterra objects to the Interrogatories to the extent they prematurely seek information in advance of the sequenced disclosures called for by the Court's Scheduling Order entered in this case, and any applicable Local Rules.

13. Volterra objects to the Interrogatories to the extent they call for a legal conclusion.

14. Volterra objects to the Interrogatories to the extent they seek "any" and/or "all" facts, information, or evidence in Volterra's possession, custody, or control responsive to the Interrogatories as not relevant to the claims or defenses of any party, not reasonably calculated to lead to the discovery of admissible evidence, overly broad, unduly burdensome, and as seeking discovery limited by Rule 26(b)(2)(C).

15. Volterra objects to the Interrogatories to the extent that they require Volterra to conduct a search for information that would be unreasonably burdensome and costly to perform,

inter alia, under Federal Rule 26(b)(2). Volterra will produce electronically stored information that is reasonably accessible in accordance with Federal Rules, including Federal Rule 26(b)(2)(B).

16. The General Objections and Specific Objections are made as to matters that are clearly objectionable on the face of the Interrogatories. Volterra makes the objections without prejudice and without waiver of its right to object on any grounds to any of the Interrogatories.

17. Volterra objects to the "Instructions" to the extent they seek to impose any presumptions, admissions, or conclusions as to the applicability of Federal Rule of Civil Procedure 37. Volterra's investigation is ongoing, and Volterra's responses to these Interrogatories are made without prejudice to Volterra's right to introduce any and all documents and other evidence of any kind in the proceedings of this action.

18. Volterra incorporates by reference the foregoing General Objections in its Specific Response to each Interrogatory. Volterra may repeat a General Objection for emphasis or some other reason. The failure to repeat any such objection with respect to a particular Interrogatory does not waive that objection. Moreover, Volterra does not waive its right to amend its objections. Any specific objections to the following Interrogatories are in addition to, and not in lieu of, the foregoing objections.

DEFINITION OBJECTIONS

1. Volterra objects to the definitions of "You," "Your," "Plaintiff," and "Volterra" as vague, ambiguous, overly broad, and unduly burdensome to the extent that those definitions (in combination with the individual Interrogatories): (i) seek to encompass information that is not relevant, proportional to the needs of the case, or reasonably calculated to lead to the discovery of admissible evidence; (ii) are not reasonably limited in time or scope; (iii) seek to encompass

information not within Volterra's possession, custody, or control; and/or (iv) seek to encompass information protected from disclosure by the attorney-client privilege, the work product doctrine, the common interest privilege, Fed. R. Civ. P. 26(b)(4)(A), or any other applicable privilege or immunity.

2. Volterra objects to the definitions of "Defendant" and "MPS" to the extent they do not include "predecessors-in-interest, parents, subsidiaries, joint ventures, affiliates, and other legal entities that are wholly or partially owned or controlled by [MPS] either directly or indirectly, and the principals, directors, officers, owners, members, representatives, employees, agents, consultants, accountants, and attorneys of these same entities."

3. Volterra objects to the definition of "Volterra Covered Product(s)" on the grounds and to the extent that it is overly broad, unduly burdensome, vague, ambiguous, unclear, and encompasses information that is not relevant to the claims or defenses of any party to this action or reasonably calculated to lead to the discovery of admissible evidence in this action.

SPECIFIC OBJECTIONS AND RESPONSES TO INTERROGATORIES

Subject to its Objections to Definitions incorporated by reference, as well as the specific objections set forth below, Volterra responds to Monolithic's interrogatories as follows:

INTERROGATORY NO. 1:

For each Volterra Asserted Patent that You contend Defendant has willfully infringed, describe in detail and identify the factual and legal bases for Your contention, and identify all facts, evidence, and Documents supporting such contention.

RESPONSE TO INTERROGATORY NO. 1:

In addition to the General Objections and Definition Objections, which are incorporated by reference as though fully set forth herein, Volterra objects to this Interrogatory to the extent it

seeks information protected by the attorney-client privilege, work product doctrine, or any other applicable privilege or immunity from discovery. Volterra further objects to this Interrogatory as vague, ambiguous, overbroad, and unduly burdensome with respect to the terms "all facts, evidence, and Documents." Volterra further objects to this Interrogatory as premature because the vast majority of information related to Monolithic's willful infringement is uniquely in Monolithic's possession and Monolothic has not responded to discovery at the time of this response. Subject to and without waiving the foregoing objections, Volterra responds as follows:

Monolithic has had knowledge of the '986 patent and that its activities infringe the '986 patent long before the filing of this action. Specifically, the follow activities demonstrate Monolithic's *presuit* knowledge and intent regarding the '986 patent:

a. In approximately June 2019, Monolithic engaged in communications with potential customer, [redacted] In these discussions, Monolithic specifically discussed the Volterra patent portfolio related to coupled inductor based voltage converters. Monolithic expressed to [redacted] that it did not feel that the Volterra patents would be a problem for at least the reason that the patents would be expiring soon. The '986 patent is the first patent to expire in the Volterra patent portfolio related to coupled inductor based voltage converters. As such, the reference by Monolithic to expiring Volterra patents evidences Monolithic's knowledge and intent regarding at least the '986 patent.

b. In the third quarter of 2019, prior to the filing of the Complaint, Monolithic contacted component manufacturer [redacted] and requested that [redacted] develop a coupled inductor for Monolithic's use. In response to Monolithic's request, [redacted] asked Monolithic about Volterra's

coupled inductor patents and asked if Monolithic could satisfy [redacted] that there would not be infringement of Volterra patents related to voltage converters based on a coupled inductor architecture.

c. During the course of Monolithic's work with potential customer [redacted] in 2018, an [redacted] engineer raised Volterra's coupled inductor patents with Monolithic.

d. Technical publications by Monolithic engineers, including at least one involved with presenting Monolithic's power solutions at APEC conferences, show that Monolithic specifically was familiar with Volterra's coupled inductor patents, including the '986 patent. This is not surprising since Volterra's coupled inductor patents are widely known in this industry. Multiple Monolithic senior engineers have written technical papers in which they discussed the '986 patent and the Volterra patented designs at length.

i. Jinghai Zhou is a senior engineer for Monolithic with extensive knowledge of the '986 patent and Volterra's patented designs since 2005. According to Mr. Zhou's LinkedIn profile (https://www.linkedin.com/in/jinghai-zhou-4b9b5b30/), he has been continuously employed by Monolithic since February 2006 and held the title of Director of Applications until January 2019 when he became a Senior Director. [redacted] Mr. Zhou has also been involved

with presenting Monolithic's power solutions at APEC conferences, as illustrated when Mr. Zhou gave a presentation for the 2020 IEEE Applied Power Electronics Conference and Exposition ("APEC 2020") on March 17, 2020 entitled "Scalable 2-Stage 48V to POL Power Delivery for Data Centers." Mr. Zhou also has extensive familiarity with the '986 patent as illustrated in his dissertation. In Mr. Zhou's April 22, 2005 Dissertation, entitled "High Frequency, High Current Density Voltage Regulators," he analyzed what he called the "scalable multi-phase surface mount coupling inductor structure *proposed by Volterra*." To illustrate what he meant by the structure proposed by Volterra, Mr. Zhou *cited the '986 patent* as well as multiple related papers by the inventors of the '986 patent. An excerpt from the dissertation along with the citations is shown below:

Based on this understanding, a scalable multi-phase surface mount coupling inductor structure is proposed by [77, 78], as shown in Figure 4.15. For each phase, there is one copper winding around the H-core so that the leg for leakage flux path (center leg in Figure 4.1) is eliminated.

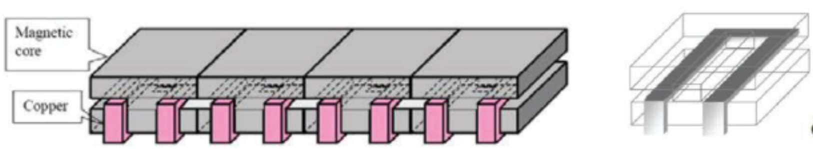


Figure 4.15 A scalable multi-phase surface mount coupling inductor structure proposed by Volterra in [77]

[76] Jieli Li; Sullivan, C.R.; Schultz, A., "Coupled-inductor design optimization for fast-response low-voltage DC-DC converters," APEC 2002. Seventeenth Annual IEEE, Volume: 2, 10-14 March 2002, Pages: 817 – 823.

[77] Jieli Li, Schultz, A., Stratakos, A., Sullivan, C.R., "Using Coupled Inductors to Enhance Transient Performance of Multi-Phase Buck Converters," APEC 2004. Seventeenth Annual IEEE, Volume: 2, 10-14 March 2002, Pages: 817 – 823.

[78] Aaron M. Schultz, Charles R. Sullivan, "Voltage Converter with Coupled Inductive Windings, and Associated Methods," U. S. Patent 6362986 B1, March 26, 2002.

ii. Yan Dong was another Monolithic engineer with long-standing extensive knowledge of the '986 patent and the patented Volterra designs, further confirming the widely known nature of the Volterra patents at Monolithic and throughout the industry. According to Mr. Dong's LinkedIn profile, he began working at Monolithic in November 2008 and held the title of Power Architect/Senior Design Engineer until September 2016. (https://www.linkedin.com/in/yan-dong-56583639/). In Mr. Dong's Dissertation, entitled "Investigation of Multiphase Coupled-Inductor Buck Converters in Point-o -Load Applications," he discussed Volterra's inventions and cited papers written by the inventors of the '986 patent.

[40] J. Li, A. Stratakos, A Schultz, C. R. Sullivan, "Using coupled-inductors to enhance transient performance of multi-phase buck converters," in Proc. IEEE APEC '04, Feb. 22-26, 2004, Anaheim, CA, pp. 1289–1293.

[41] Jieli Li, Charles R. Sullivan, Aaron Schultz, "Coupled-inductor design optimization for fast-response low-voltage DC-DC converters", in Proceedings of APEC 2002 - Applied Power Electronics Conf., pp. 817–823 vol.2.

[42] A. M. Schultz and C. R. Sullivan, "Voltage converter with coupled inductive windings and associated methods", U.S. Patent 6,362,986, Mar. 26, 2002, Volterra Semiconductor Corp.

e. Finally, Volterra realleges that Monolithic's knowledge and intent is further demonstrated by post-suit activity. By at least December 9, 2019, Volterra disclosed, at least by filing its Complaint, the existence of the '986 patent and identified at least some of Monolithic's and others' activities that infringe the '986 patent. Thus, based on this disclosure, Monolithic had knowledge of the '986 patent and that its activities infringe the '986 patent since at least December 9, 2019. Based on Volterra's disclosures, Monolithic has also known or should have known since at least December 9, 2019 that its customers, distributors,

suppliers, and other purchasers of the Accused Products are infringing the '986 patent at least because Monolithic has known that it is infringing the '986 patent.

Monolithic has had knowledge of the '408 patent and that its activities infringe the '408 patent long before the filing of this action. Specifically, the follow activities demonstrate Monolithic's *presuit* knowledge and intent regarding the '408 patent:

a. As described above with respect to the '986 patent, Monolithic specifically discussed the Volterra patent portfolio related to coupled inductor based voltage converters with [redacted] in approximately June 2019. Monolithic expressed to [redacted] that it did not feel that the Volterra patents would be a problem for at least the reason that the patents would be expiring soon. The '986 patent is the first patent to expire in the Volterra patent portfolio related to coupled inductor based voltage converters. The '408 patent shares a common inventor with the '986 patent and will expire 25 months after the '986 patent. As such, the reference by Monolithic to expiring Volterra patents evidences Monolithic's knowledge and intent regarding at least the '408 patent.

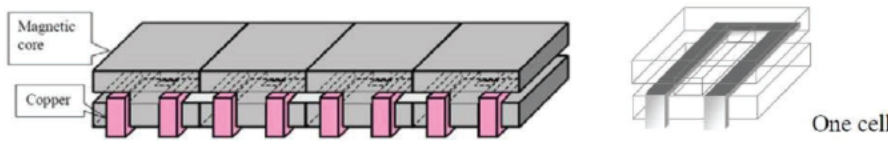
b. As described above with respect to the '986 patent, in the third quarter of 2019, prior to the filing of the Complaint, component manufacturer [redacted] asked Monolithic about Volterra's coupled inductor patents and asked if Monolithic could satisfy [redacted] that there would not be infringement of the Volterra patents related to voltage converters based on a coupled inductor architecture.

c. As described above with respect to the '986 patent, during the course of Monolithic's work with potential customer [redacted] in 2018, an [redacted] engineer raised Volterra's coupled inductor patents with Monolithic.

d. As described above with respect to the '986 patent, technical publications by Monolithic engineers, including at least one involved with presenting Monolithic's power solutions at APEC conferences, show that Monolithic specifically was familiar with Volterra's coupled inductor patents. This is not surprising because Volterra's coupled inductor patents are widely known in this industry. Multiple Monolithic senior engineers have written technical papers in which they discussed the Volterra patented designs at length.

i. As discussed above with respect to the '986 patent, [redacted] Mr. Zhou's dissertation analyzed what he called the "scalable multi-phase surface mount coupling inductor structure *proposed by Volterra*." To illustrate what he meant by the structure proposed by Volterra, Mr. Zhou cited the '986 patent. The '408 patent shares an inventor with the '986 patent and devotes multiple paragraphs to the '986 patent in the Background of the Invention section, indicating that the patents are related and would be discussed together. Mr. Zhou's dissertation also cited multiple related papers by the inventors of the '986 patent, including Charles R. Sullivan—an inventor of the '408 patent. The dissertation also cites to several other papers by Mr. Sullivan, evidencing that Mr. Zhou was very familiar with his work. An excerpt from the dissertation along with the citations is shown below:

Based on this understanding, a scalable multi-phase surface mount coupling inductor structure is proposed by [77, 78], as shown in Figure 4.15. For each phase, there is one copper winding around the H-core so that the leg for leakage flux path (center leg in Figure 4.1) is eliminated.



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[76] Jieli Li; Sullivan, C.R.; Schultz, A., "Coupled-inductor design optimization for fast-response low-voltage DC-DC converters," APEC 2002. Seventeenth Annual IEEE, Volume: 2, 10-14 March 2002, Pages: 817 – 823.

[77] Jieli Li, Schultz, A., Stratakos, A., Sullivan, C.R., "Using Coupled Inductors to Enhance Transient Performance of Multi-Phase Buck Converters," APEC 2004. Seventeenth Annual IEEE, Volume: 2, 10-14 March 2002, Pages: 817 – 823.

[78] Aaron M. Schultz, Charles R. Sullivan, "Voltage Converter with Coupled Inductive Windings, and Associated Methods," U. S. Patent 6362986 B1, March 26, 2002.

[98] L. Daniel, C. R. Sullivan and S. R. Senders, "Design of Microfabricated Inductors," Proc. IEEE PESC, 1996, pp. 1447-1455.

[120] C.J. Mehas, K.D. Coonley and C.R. Sullivan, "Converter and inductor design for fast-response microprocessor power delivery," in Proc. IEEE PESC, 2000, pp. 1621-1626.

ii. Mr. Dong's Dissertation discussed Volterra's inventions and cited papers written by Mr. Sullivan. Indeed, Mr. Dong recognized that "C. Sullivan developed the **n-phase coupled-inductor buck converter** analysis when the duty cycle D is less than 1/n." The '408 patent is entitled "Method for making magnetic components with **N-phase coupling**, and related inductor structures" and "relates to construction of a **coupled inductor within a multi-phase DC-to-DC converter**." Mr. Dong also analyzed "C. Sullivan's two-phase coupled-inductor structure" and "C. Sullivan's

three-phase coupled-inductor and its magnetic paths." Like Mr. Zhou, Mr. Dong's dissertation cites to several papers by Mr. Sullivan, evidencing that Mr. Zhou was very familiar with his work.

> [14] G. J. Mehas, K. D. Coonley and C. R. Sullivan, "Converter and inductor design for fast-response microprocessor power delivery," Proc. of IEEE PESC, 2001, pp. 1621-1626.
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> [40] J. Li, A. Stratakos, A Schultz, C. R. Sullivan, "Using coupled-inductors to enhance transient performance of multi-phase buck converters," in Proc. IEEE APEC '04, Feb. 22-26, 2004, Anaheim, CA, pp. 1289–1293.
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> [54] A. Hoke and C. R. Sullivan, "An Improved two-dimensional numerical modeling method for E-core transformers," in Proc. IEEE APEC '02, Mar. 10-14, 2002, Dallas, TX, pp. 151 - 157.

e. Finally, Volterra realleges that Monolithic's knowledge and intent is further demonstrated by post-suit activity. By at least December 9, 2019, Volterra disclosed, at least by filing its Complaint, the existence of the '408 patent and identified at least some of Monolithic's and others' activities that infringe the '408 patent. Thus, based on this disclosure, Monolithic had knowledge of the '408 patent and that its activities infringe the '408 patent since at least December 9, 2019. Based on Volterra's disclosures, Monolithic has also known or should have known since at least December 9, 2019 that its customers, distributors, suppliers, and other purchasers of the Accused Products are infringing the '408 patent at least because Monolithic has known that it is infringing the '408 patent.

Monolithic has had knowledge of the '955 patent and that its activities infringe the '955 patent long before the filing of this action. Specifically, the follow activities demonstrate Monolithic's *presuit* knowledge and intent regarding the '955 patent:

a. As described above with respect to the '986 and '408 patents, Monolithic specifically discussed the Volterra patent portfolio related to coupled inductor based voltage converters with [redacted] in approximately June 2019. Monolithic expressed to [redacted] that it did not feel that the Volterra patents would be a problem for at least the reason that the patents would be expiring soon. The '986 patent is the first patent to expire in the Volterra patent portfolio related to coupled inductor based voltage converters. The '955 patent shares a common inventor with the '986 patent and will expire 21 months after the '986 patent. As such, the reference by Monolithic to expiring Volterra patents evidences Monolithic's knowledge and intent regarding at least the '955 patent.

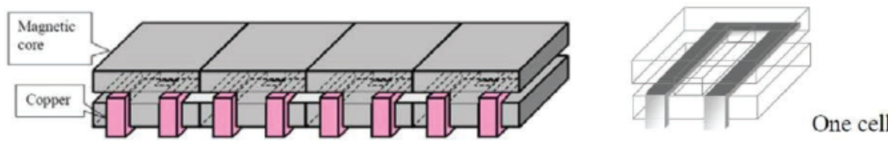
b. As described above with respect to the '986 and '408 patents, in the third quarter of 2019, prior to the filing of the Complaint, component manufacturer [redacted] asked Monolithic about Volterra's coupled inductor patents and asked if Monolithic could satisfy [redacted] that there would not be infringement of the Volterra patents related to voltage converters based on a coupled inductor architecture.

c. As described above with respect to the '986 and '408 patents, during the course of Monolithic's work with potential customer [redacted] in 2018, an [redacted] engineer raised Volterra's coupled inductor patents with Monolithic.

d. As described above with respect to the '986 and '408 patents, technical publications by Monolithic engineers, including at least one involved with presenting Monolithic's power solutions at APEC conferences, show that Monolithic specifically was familiar with Volterra's coupled inductor patents. This is not surprising because Volterra's coupled inductor patents are widely known in this industry. Multiple Monolithic senior engineers have written technical papers in which they discussed the Volterra patented designs at length.

i. As discussed above with respect to the '986 and '408 patents, [redacted] Mr. Zhou's dissertation analyzed what he called the "scalable multi-phase surface mount coupling inductor structure *proposed by Volterra*." To illustrate what he meant by the structure proposed by Volterra, Mr. Zhou cited the '986 patent. The '955 patent shares an inventor with the '986 patent and devotes multiple paragraphs to the '986 patent in the Background of the Invention section, indicating that the patents are related and would be discussed together. Mr. Zhou's dissertation also cited multiple related papers by the inventors of the '986 patent, including Charles R. Sullivan—an inventor of the '955 patent. The dissertation also cites to several other papers by Mr. Sullivan, evidencing that Mr. Zhou was very familiar with his work. An excerpt from the dissertation along with the citations is shown below:

Based on this understanding, a scalable multi-phase surface mount coupling inductor structure is proposed by [77, 78], as shown in Figure 4.15. For each phase, there is one copper winding around the H-core so that the leg for leakage flux path (center leg in Figure 4.1) is eliminated.



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ii. Mr. Dong's Dissertation discussed Volterra's inventions and cited papers written by Mr. Sullivan. Indeed, Mr. Dong recognized that "C. Sullivan developed the **n-phase coupled-inductor buck converter** analysis when the duty cycle D is less than 1/n." The '955 patent is entitled "Method for making magnetic components with **N-phase coupling**, and related inductor structures" and "relates to construction of a **coupled inductor within a multi-phase DC-to-DC converter**." Mr. Dong also analyzed "C. Sullivan's two-phase coupled-inductor structure" and "C. Sullivan's

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Pursuant to Rule 33(d) of the Federal Rules of Civil Procedure, Volterra will identify and produce documents under Rule 33(d) that contain relevant and non-privileged information relevant to this Interrogatory. Volterra further states that its response will be based in part on, but not limited to, yet to be produced information from Monolithic. Discovery is ongoing, and Volterra reserves its right to supplement its response based on information to be produced by Monolithic and in accordance with the Federal and Local Rules.

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 1 (9/7/2021):

Subject to and without waiving the foregoing objections, Volterra supplements its response as follows:

Volterra identifies the deposition transcripts of Dawson Huang, Bernie Blegen, Roland Tso and Jinghai Zhou as having information relevant to this Interrogatory. Volterra further identifies the upcoming deposition of Ahmed Abou-Alfotouh as having information relevant to this Interrogatory.

INTERROGATORY NO. 2:

For each Accused Product and Volterra Asserted Claim, describe in detail and identify the factual and legal bases for Your claim for damages to which You contend You are entitled as a result of Defendant's alleged infringement, including without limitation, whether Your damages claims are based on lost profits, a reasonably royalty, or other damages theory, any royalty rate, royalty base, lost profits, disgorgements, enhanced damages, attorney's fees, or costs that You contend are appropriate, Your products that you contend compete with the Accused Products, noninfringing alternatives, the date You contend the hypothetical negotiation would have commenced with respect to each Volterra Asserted Patent, the time period for which You contend You are entitled to collect damages from Defendant due to any alleged infringement of each Volterra Asserted Patent, and whether the royalty base is based on the value of the entire product

EXHIBIT 7

IN THE UNITED STATES DISTRICT COURT

FOR THE DISTRICT OF DELAWARE

VOLTERRA SEMICONDUCTOR LLC, Plaintiff, v. MONOLITHIC POWER SYSTEMS, INC., Defendant.	))))))))))	C.A. No. 19-2240-CFC-SRF **HIGHLY CONFIDENTIAL - ATTORNEYS' EYES ONLY**

MONOLITHIC POWER SYSTEMS, INC.'S FIFTH SUPPLEMENTAL OBJECTIONS AND RESPONSES TO VOLTERRA SEMICONDUCTOR LLC'S INTERROGATORIES (NOS. 1-28)

Pursuant to Federal Rules of Civil Procedure 26 and 33 and the District of Delaware Civil Local Rules 26.1 and 26.2, Defendant Monolithic Power Systems, Inc. ("MPS") hereby provides the following fourth supplemental objections and responses to Plaintiff Volterra Semiconductor LLC's ("Volterra") Interrogatories (Nos. 1-28) (each, a "Interrogatory," collectively the "Interrogatories") as set forth below.

GENERAL OBJECTIONS

The following general objections are incorporated by reference into Defendant's responses to each and every Interrogatory

1. Defendant objects to each Interrogatory to the extent that it seeks or imposes requirements or obligations on Defendant that are inconsistent with those set forth in the Federal Rules of Civil Procedure, the District of Delaware Civil Local Rules, or any other applicable rules or orders governing this case, including the scope of discovery agreed to by the parties, written or otherwise.

2. Defendant's responses and objections are based upon information currently known to it through reasonable investigation thus far, and are subject to amendment, supplementation, and/or other modification. Discovery in this matter is ongoing, and during the course of subsequent discovery, Defendant may become aware of additional information that may be responsive to the Interrogatories. Defendant reserves the right to amend, supplement, or otherwise modify these responses and objections if additional information is discovered. By providing these responses and objections, Defendant does not, and does not intend to, waive its right to rely on evidence or information that is subsequently discovered through its continuing investigation and/or included in amended, supplemental, or otherwise modified responses. In addition, these responses and objections are made without prejudice to Defendant's right to present additional evidence or contentions at trial based upon information hereafter obtained or developed.

3. Defendant objects to each Interrogatory to the extent it seeks information protected from disclosure by the attorney-client privilege, patent agent privilege, work product doctrine, or any other applicable privilege or protection from discovery. Defendant further objects to each Interrogatory to the extent that it seeks information prepared in anticipation of litigation or for trial of this or any matter that is subject to protection under Rule 26 of the Federal Rules of Civil Procedure, and related case law.

4. Defendant objects to each Definition, Instruction, and Interrogatory that uses the term "Accused Product(s)" (as defined in Definition No. 11) or "product" as outside the scope of this litigation to the extent is seeks discovery of any Defendant product that does not fall under the scope of "Accused Products" as defined at Paragraph 18 of Volterra's Second Amended Complaint ("SAC"), D.I. 71.

5. Defendant objects to each Definition, Instruction, and Interrogatory to the extent the documents or information requested are not in Defendant's possession, custody, and/or control.

6. Defendant objects to each Interrogatory that encompasses multiple subparts, which pursuant to the District of Delaware Civil Local Rule 26.1(a), count towards Plaintiffs' discovery limits as set forth in Fed. R. Civ. P. 33(a)(1).

7. Defendant objects to each Definition, Instruction, and Interrogatory to the extent it seeks information that contains confidential business information, trade secrets, and/or proprietary information of a party in this litigation or a third party. Defendant will only produce such documents and/or pursuant to the Protective Order in this litigation, D.I. 80, and in accordance with the District of Delaware Local Rule 26.2.

8. Defendant objects to each Definition, Instruction, and Interrogatory to the extent it seeks to impose obligations on Defendant that are inconsistent with and/or beyond the scope of those imposed or authorized by the Federal Rules of Civil Procedure, the Local Rules of this Court, or any governing case law.

9. Defendant objects to each Definition, Instruction, and Interrogatory with an open-ended time period and, unless specifically stated otherwise, Defendant will limit its answers to providing information from the relevant time period.

10. Defendant objects to each Definition, Instruction, and Interrogatory that uses any of the terms "Document(s)," "Thing(s)," "Communication," "Person(s)," "Entity," or "Entities" as vague, overbroad, ambiguous, unduly burdensome to the extent it seeks information that is not relevant to any party's claim or defense and proportional to the needs of the case, seeking information protected from disclosure by the attorney-client privilege, the attorney work product,

or another applicable privilege and/or immunity, and seeking information that is not reasonably accessible to Defendant upon reasonable diligence.

11. Defendant objects to each Definition, Instruction, and Interrogatory to the extent it seeks information from or the production of documents from the internal work product files of attorneys representing or advising Defendant, Defendant objects generally to either the production or the listing of such documents on a withheld-document list.

12. Defendant objects to each Definition, Instruction, and Interrogatory that uses "identify" as applied to a document, thing, or information as overly broad and unduly burdensome to the extent it seeks information that is irrelevant to the present action.

13. Defendant objects to each Definition, Instruction, and Interrogatory that uses "identify" as applied to a person as overly broad and unduly burdensome to the extent it seeks information that is irrelevant to the present action or protected by a right of privacy.

14. Defendant objects to each Definition, Instruction, and Interrogatory that uses any of the phrases "relating to," "related to," or "constituting" as vague, ambiguous, indefinite, overly broad, unduly burdensome, seeking information that is not relevant to any party's claim or defendant and not proportional to the needs of the case, seeking information protected from disclosure by the attorney-client privilege, the attorney work product, or another applicable privilege and/or immunity, and seeking information that is not within Defendant's possession, custody, or control and is not reasonably accessible to Defendant upon reasonable diligence.

15. Defendant objects to Plaintiff's Instructions as vague, ambiguous, indefinite, overbroad, unduly burdensome, seeking improperly to expand Defendant's obligations beyond the scope required by the local rules and the Federal Rules of Civil Procedure, seeking the production of information that is not relevant to any party's claim or defense and proportional to the needs of

the case, seeking the production of information protected from disclosure by the attorney-client privilege, the attorney work product, or another applicable privilege and/or immunity, and seeking the production of information that is not within Defendant's possession, custody, or control and is not reasonably accessible to Defendant upon reasonable diligence. Defendant additionally objects to Instruction No. 6 to the extent it requires Defendant to produce a privilege log.

16. Nothing in these responses shall be construed to waive rights or objections, which are otherwise available to Defendant, nor shall Defendant's response to any of these Interrogatories be deemed an admission of relevancy, materiality, or admissibility in evidence of the Interrogatory or of the responses thereto. Defendant's responses are made without waiving (1) the right to object on any basis permitted by law to the use of any information provided herein, for any purpose, in whole or in part, in any subsequent proceeding in this action or any other action; and (2) the right to object on any basis permitted by law to any other discovery requests or proceedings involving or relating to the subject matter of these responses.

FOURTH SUPPLEMENTAL OBJECTIONS AND RESPONSES

INTERROGATORY NO. 1

Identify each Defendant Product.

RESPONSE TO INTERROGATORY NO. 1 (DATED OCT. 14, 2020)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant further objects to each Definition, Instruction, and Interrogatory that uses the term "Accused Product(s)" (as defined in Definition No. 11) or "product" as outside the scope of this litigation to the extent is seeks discovery of any Defendant product that does not fall under the scope of "Accused Products" as defined at Paragraph 18 of Volterra's Second Amended Complaint ("SAC"), D.I. 71. Defendant objects to this Interrogatory to the extent it seeks information protected from disclosure by the attorney-client privilege, work product immunity, common interest, or any other applicable privilege or protection. Defendant further objects to this Interrogatory to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant objects to this Interrogatory to the extent the Interrogatory is unbounded in time. Defendant objects to this Interrogatory to the extent the documents or information requested are publicly available and/or equally available to the requesting party. Defendant further objects to this Interrogatory to the extent it requests customer and/or sampler information that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent the documents or information requested are not in Defendant's possession, custody, and/or control. Defendant objects to this Interrogatory to the extent it seeks disputed legal and factual contentions, and testimony such as Invalidity Contentions, claim constructions, and other such reports

identified by the Scheduling Order; Defendant will disclose its expert's opinions, Invalidity Contentions, claim constructions, and other such documents at the appropriate time as set by the Discovery and Scheduling Order, D.I. 69. Defendant also objects to this Interrogatory as encompassing multiple subparts, which pursuant to the District of Delaware Civil Local Rule 26.1(a), count towards Plaintiffs' discovery limits as set forth in Fed. R. Civ. P. 33(a)(1).

Subject to and without waiving its objections, Defendant responds as follows: MPS's 48V-1V Power Solution for CPU, SoC or ASIC Controller.

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 1 (SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Oct. 14, 2020, Defendant responds as follows:

MPS identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 2

For each Defendant Product identified in response to Interrogatory No. 1, describe in detail the development of the product from conception to commercialization, and identify the individuals involved in the development and their roles, and the time frame and location of the development work by such individuals.

RESPONSE TO INTERROGATORY NO. 2 (DATED OCT. 14, 2020)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant further objects to this Interrogatory to the extent it seeks information protected from disclosure by the attorney-client privilege, work product immunity, common interest, or any other applicable privilege or protection. Defendant objects to this Interrogatory

because it seeks information that is outside the scope of this litigation. Defendant further objects to this Interrogatory to the extent it requests customer and/or sampler information that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent the documents or information requested are publicly available and/or equally available to the requesting party. Defendant objects to this Interrogatory to the extent the documents or information requested are not in Defendant's possession, custody, and/or control. Defendant objects to this Interrogatory to the extent it seeks disputed legal and factual contentions, and testimony such as Invalidity Contentions, claim constructions, and other such reports identified by the Scheduling Order; Defendant will disclose its expert's opinions, Invalidity Contentions, claim constructions, and other such documents at the appropriate time as set by the Discovery and Scheduling Order, D.I. 69. Defendant further objects to this Interrogatory to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant also objects to this Interrogatory as encompassing multiple subparts, which pursuant to the District of Delaware Civil Local Rule 26.1(a), count towards Plaintiffs' discovery limits as set forth in Fed. R. Civ. P. 33(a)(1).

Subject to and without waiving its objections, Defendant responds as follows:

Defendant's investigation is ongoing and Defendant incorporates by reference its Initial Disclosures pursuant to Rule 26. In addition, and pursuant to Federal Rule of Civil Procedure 33(d), Defendant will produce non-privileged documents located after a reasonably diligent search from which additional information responsive to the non-objectionable scope of this interrogatory can be derived.

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 2 (SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Oct. 14, 2020, Defendant responds as follows:

MPS identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 3

Describe when and how You first became aware of each Asserted Patent, and what actions,if any, You took in response, and identify all Communications relating to that first awareness or the actions taken in response.

RESPONSE TO INTERROGATOR NO. 3 (DATED OCT. 14, 2020)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant objects to the phrases "all" Communications as overly broad, unduly burdensome, not reasonably calculated to lead to the discovery of admissible evidence, and not proportional to the needs of this litigation. Defendant objects to this Interrogatory to the extent it seeks information protected from disclosure by the attorney-client privilege, work product immunity, common interest, or any other applicable privilege or protection. Defendant objects to this Interrogatory because it seeks information that is outside the scope of this litigation. Defendant objects to this Interrogatory to the extent the documents or information requested are publicly available and/or equally available to the requesting party. Defendant objects to this Interrogatory to the extent the documents or information requested are not in Defendant's possession, custody, and/or control. Defendant further objects to this Interrogatory to the extent it requests customer

and/or sampler information that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent it seeks disputed legal and factual contentions, and testimony such as Invalidity Contentions, claim constructions, and other such reports identified by the Scheduling Order; Defendant will disclose its expert's opinions, Invalidity Contentions, claim constructions, and other such documents at the appropriate time as set by the Discovery and Scheduling Order, D.I. 69. Defendant further objects to this Interrogatory to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant also objects to this Interrogatory as encompassing multiple subparts, which pursuant to the District of Delaware Civil Local Rule 26.1(a), count towards Plaintiffs' discovery limits as set forth in Fed. R. Civ. P. 33(a)(1).

Subject to and without waiving its objections, Defendant responds as follows:

[redacted]

As for the two other Asserted Patents, the '408 patent and the '955 patent, Defendant confirms it first became aware of them as of the service date of the Complaint. D.I. 5.

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 3 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Oct. 14, 2020, Defendant responds as follows:

MPS identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 4

Identify all Communications with any third-party relating to any Asserted Patent.

RESPONSE TO INTERROGATORY NO. 4 (DATED OCT. 14, 2020)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant further objects to the phrases "all" Communications and "any" third-party as overly broad, unduly burdensome, not reasonably calculated to lead to the discovery of admissible evidence, and not proportional to the needs of this litigation. Defendant objects to the phrase "relating to" as indefinite, vague, ambiguous, overly broad, and unduly burdensome to the extent it seeks the production of information that is not relevant to any claim or defense of any party in this litigation or is not proportional to the needs of this litigation. Defendant objects to this Interrogatory as overly broad and unduly burdensome on the ground that it is unbounded in time. Defendant further objects to this Interrogatory to the extent it seeks information or documents protected from disclosure by attorney-client privilege, patent agent privilege, work product doctrine, or any other applicable privilege or protection from discovery. Defendant further objects to this Interrogatory to the extent it prematurely seeks disputed legal and factual contentions, and testimony such as Invalidity Contentions, claim constructions, and other such reports identified by the Scheduling Order; Defendant will disclose its expert's opinions, Invalidity Contentions, claim constructions, and other such documents at the appropriate time as set by the Discovery and Scheduling Order, D.I. 69. Defendant further objects to this Interrogatory to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant further objects to this

Interrogatory to the extent it seeks information not in Defendant's possession, custody, or control. Defendant objects to this Interrogatory to the extent it seeks information that is publicly available and/or equally available to the requesting party. Defendant objects to this Interrogatory to the extent it requests customer and/or sampler information that is not relevant or proportional to the needs of this case.

Subject to and without waiving its objections, Defendant responds as follows:

Defendant's investigation is ongoing and Defendant incorporates by reference its Initial Disclosures pursuant to Rule 26. In addition, and pursuant to Federal Rule of Civil Procedure 33(d), Defendant will produce non-privileged documents located after a reasonably diligent search from which additional information responsive to the non-objectionable scope of this interrogatory can be derived.

Defendant's investigation is ongoing. Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 4 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Oct. 14, 2020, Defendant responds as follows:

Defendant identifies at least the following documents as Communications with third parties related to the Asserted Patents in this litigation:

- [redacted]
- [redacted]
- [redacted]
- [redacted]

[redacted] [redacted]

[redacted] [redacted]

[redacted] [redacted]

[redacted] [redacted]

[redacted] [redacted]

[redacted] [redacted]

[redacted] [redacted]

Defendant further identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

<u>INTERROGATORY NO. 5</u>

For each Defendant Product, describe where, by which Persons or Entities, and over what period it was manufactured, used, sold, offered for sale, and/or imported into the United States, and provide financial information relating to each Defendant Product, including on a monthly basis (for both the United States and worldwide), sales volume (i.e., quantity of units sold), revenue, costs of goods sold, other fixed or variable costs, and gross and net profits, and identify all supporting Documents and Persons most knowledgeable about the subject matter of Your response.

<u>RESPONSE TO INTERROGATORY NO. 5 (DATED OCT. 14, 2020)</u>

Defendant incorporates all of its objections and reservations of rights as specifically alleged herein. Defendant further objects to the phrase “all” supporting Documents and Persons as overly broad, unduly burdensome, not reasonably calculated to lead to the discovery of admissible evidence, and not proportional to the needs of this litigation. Defendant objects to the phrases “most knowledgeable”, “sales volume,” “revenue,” and “subject matter of Your response” as

vague and ambiguous. Defendant objects to the phrase "relating to" as indefinite, vague, ambiguous, overly broad, and unduly burdensome to the extent it seeks the production of information that is not relevant to any claim or defense of any party in this litigation or is not proportional to the needs of this litigation. Defendant objects to this Interrogatory as overly broad, unduly burdensome, and not proportional to the needs of this litigation to the extent it seeks financial information for each Defendant Product that is made, used, sold, or offered for sale by MPS outside the United States. Defendant objects to this Interrogatory as overly broad and unduly burdensome on the ground that it is unbounded in time. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant further objects to this Interrogatory to the extent it seeks information or documents protected from disclosure by attorney-client privilege, patent agent privilege, work product doctrine, or any other applicable privilege or protection from discovery. Defendant further objects to this Interrogatory to the extent it prematurely seeks disputed legal and factual contentions, and testimony such as Invalidity Contentions, claim constructions, and other such reports identified by the Scheduling Order; Defendant will disclose its expert's opinions, Invalidity Contentions, claim constructions, and other such documents at the appropriate time as set by the Discovery and Scheduling Order, D.I. 69. Defendant further objects to this Interrogatory to the extent it seeks information not in Defendant's possession, custody, or control. Defendant further objects to this Request to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it seeks information of third parties that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent it seeks information that is publicly available and/or equally available to the requesting party. Defendant also objects to this Interrogatory as

encompassing multiple subparts, which pursuant to the District of Delaware Civil Local Rule 26.1(a), count towards Plaintiffs' discovery limits as set forth in Fed. R. Civ. P. 33(a)(1).

Subject to and without waiving its objections, Defendant responds as follows

Defendant's investigation is ongoing and Defendant incorporates by reference its Initial Disclosures pursuant to Rule 26. In addition, and pursuant to Federal Rule of Civil Procedure 33(d), Defendant will produce non-privileged documents located after a reasonably diligent search from which additional information responsive to the non-objectionable scope of this interrogatory can be derived.

Defendant's investigation is ongoing. Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 5 (DATED AUG. 31, 2021)

Subject to and without waving its previous objections raised on October 14, 2020, Defendant responds as follows

[redacted]

SECOND SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 5 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on October 14, 2020, Defendant responds as follows:

Defendant incorporates by reference within its response to this interrogatory the relevant information included in its upcoming noninfringement, invalidity, and damages expert reports.

Defendant will disclose its expert reports at the appropriate time as set by the Discovery and Scheduling Order, D.I. 69 and any modifications thereto by the parties.

Defendant further identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 6

For each Defendant Product identified in response to Interrogatory No. 1, identify all competitors, and all products sold in competition to the Defendant Product.

RESPONSE TO INTERROGATORY NO. 6 (DATED OCT. 14, 2020)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant further objects to the phrases "all" competitors and "all" products as overly broad, unduly burdensome, not reasonably calculated to lead to the discovery of admissible evidence, and not proportional to the needs of this litigation. Defendant objects to the phrases "competitors" and "competition" as indefinite, vague, ambiguous, overly broad, and unduly burdensome to the extent they seek the production of information that is not relevant to any claim or defense of any party in this litigation or is not proportional to the needs of this litigation. Defendant objects to this Interrogatory as overly broad and unduly burdensome on the ground that it is unbounded in time. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant further objects to this Interrogatory to the extent it seeks information or documents protected from disclosure by attorney-client privilege, patent agent privilege, work product doctrine, or any other applicable privilege or protection from discovery. Defendant further objects to this Interrogatory to the extent it prematurely seeks disputed legal and factual contentions, and testimony such as Invalidity Contentions, claim constructions, and other such reports identified by the Scheduling Order; Defendant will disclose its expert's opinions, Invalidity

Contentions, claim constructions, and other such documents at the appropriate time as set by the Discovery and Scheduling Order, D.I. 69. Defendant further objects to this Interrogatory to the extent it seeks information not in Defendant's possession, custody, or control. Defendant further objects to this Interrogatory to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it seeks information of third parties that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent it seeks information that is publicly available and/or equally available to the requesting party. Defendant also objects to this Interrogatory as encompassing multiple subparts, which pursuant to the District of Delaware Civil Local Rule 26.1(a), count towards Plaintiffs' discovery limits as set forth in Fed. R. Civ. P. 33(a)(1).

Subject to and without waiving its objections, Defendant responds as follows

Defendant's investigation is ongoing and Defendant incorporates by reference its Initial Disclosures pursuant to Rule 26. In addition, and pursuant to Federal Rule of Civil Procedure 33(d), Defendant will produce non-privileged documents located after a reasonably diligent search from which additional information responsive to the non-objectionable scope of this interrogatory can be derived.

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 6 (DATED AUG. 31, 2021)

Subject to and without waiving its previous objections on Oct. 14, 2020, Defendant responds as follows

[redacted]

SECOND SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 6 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on October 14, 2020, Defendant responds as follows:

Defendant incorporates by reference within its response to this interrogatory the relevant information included in its upcoming noninfringement, invalidity, and damages expert reports. Defendant will disclose its expert reports at the appropriate time as set by the Discovery and Scheduling Order, D.I. 69 and any modifications thereto by the parties.

Defendant further identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 7

Identify all Communications with Your customers or potential customers, including without limitation Nvidia, Google, and Juniper, relating to an existing or proposed customer specific version of the 48V-1V Power Solution, including without limitation the Nvidia Accused Product; any component of an existing or proposed customer-specific version of the 48V-1V Power Solution; or any patent assigned to Plaintiff or Maxim.

RESPONSE TO INTERROGATORY NO. 7 (DATED FEB. 18, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant objects to the phrases "all" Communications as overly broad, unduly burdensome, not reasonably calculated to lead to the discovery of admissible evidence, and not proportional to the needs of this litigation. Defendant further objects to each Definition, Instruction, and Interrogatory that uses the term "Nvidia Accused Product" as outside the scope of this litigation to the extent is seeks discovery of any Defendant product that does not fall under the

scope of "Accused Products" as defined at Paragraph 18 of Volterra's Second Amended Complaint ("SAC"), D.I. 71. Defendant objects to this Interrogatory to the extent it seeks information protected from disclosure by the attorney-client privilege, work product immunity, common interest, or any other applicable privilege or protection. Defendant further objects to this Interrogatory to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant objects to this Interrogatory to the extent the Interrogatory is unbounded in time. Defendant objects to this Interrogatory to the extent the documents or information requested are publicly available and/or equally available to the requesting party. Defendant further objects to this Interrogatory to the extent it requests customer and/or sampler information that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent the documents or information requested are not in Defendant's possession, custody, and/or control. Defendant objects to this Interrogatory to the extent it seeks disputed legal and factual contentions, and testimony such as Invalidity Contentions, claim constructions, and other such reports identified by the Scheduling Order; Defendant will disclose its expert's opinions, Invalidity Contentions, claim constructions, and other such documents at the appropriate time as set by the Discovery and Scheduling Order, D.I. 69. Defendant also objects to this Interrogatory as encompassing multiple subparts, which pursuant to the District of Delaware Civil Local Rule 26.1(a), count towards Plaintiffs' discovery limits as set forth in Fed. R. Civ. P. 33(a)(1).

Subject to and without waiving its objections, Defendant responds as follows:

[redacted]

With regards to communications relating to the Nvidia Accused Product, Defendant's investigation is ongoing and Defendant incorporates by reference its Initial Disclosures pursuant to Rule 26. [redacted]. In addition, and pursuant to Federal Rule of Civil Procedure 33(d), Defendant will produce non-privileged documents located after a reasonably diligent search from which additional information responsive to the non-objectionable scope of this interrogatory can be derived.

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

<u>FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 7 (DATED SEPT. 7, 2021)</u>

Subject to and without waiving its previous objections raised on February 18, 2021, Defendant responds as follows:

Defendant identifies at least the following documents as Communications with MPS's customers and potential customers related to the NVIDIA Accused Product [redacted], in this litigation:

[redacted]

Defendant further identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 8

Identify all Communications with any Coupled Inductor Manufacturer relating to an existing or proposed customer-specific version of the 48V-1V Power Solution, including without limitation the Nvidia Accused Product; any Defendant Product; any MPS Defendant Product Component; any coupled inductor considered to be included in or actually included in a Defendant Product; any coupled inductor considered to be included in or actually included in an existing or proposed customer-specific version of the 48V-1V Power Solution, including without limitation the Nvidia Accused Product; or any patent assigned to Plaintiff or to Maxim.

RESPONSE TO INTERROGATORY NO. 8 (DATED FEB. 18, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant objects to the phrases "all" Communications as overly broad, unduly burdensome, not reasonably calculated to lead to the discovery of admissible evidence, and not proportional to the needs of this litigation. Defendant further objects to this Interrogatory to the extent it seeks information protected from disclosure by the attorney-client privilege, work product immunity, common interest, or any other applicable privilege or protection. Defendant objects to this Interrogatory because it seeks information that is outside the scope of this litigation. Defendant further objects to this Interrogatory to the extent it requests customer and/or sampler information that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent the documents or information requested are publicly available and/or equally available to the requesting party. Defendant further objects to each Definition, Instruction, and Interrogatory that uses the term "Nvidia Accused Product" as outside the scope of this litigation to the extent is seeks discovery of any Defendant product that does not fall under the scope of "Accused Products" as defined at Paragraph 18 of Volterra's Second Amended Complaint ("SAC"), D.I. 71. Defendant objects to this Interrogatory to the extent the documents or

information requested are not in Defendant's possession, custody, and/or control. Defendant further objects to this Interrogatory to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant also objects to this Interrogatory as encompassing multiple subparts, which pursuant to the District of Delaware Civil Local Rule 26.1(a), count towards Plaintiffs' discovery limits as set forth in Fed. R. Civ. P. 33(a)(1).

Subject to and without waiving its objections, Defendant responds as follows:

With regards to communications relating to the 48V-1V Power Solution, MPS has not sold the 48V-1V Power Solution. Therefore, no customers or potential customers exist for the 48V-1V Power Solution.

With regards to communications relating to the Nvidia Accused Product, Defendant's investigation is ongoing and Defendant incorporates by reference its Initial Disclosures pursuant to Rule 26. [redacted] In addition, and pursuant to Federal Rule of Civil Procedure 33(d), Defendant will produce non-privileged documents located after a reasonably diligent search from which additional information responsive to the non-objectionable scope of this interrogatory can be derived.

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 8 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Feb. 18, 2021, Defendant responds as follows:

Defendant identifies at least the following documents as MPS's Communications with any Coupled Inductor Manufacturer relating to the NVIDIA Accused Product, [redacted]

[redacted]

Defendant further identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 9

Explain in detail the policies, procedures, and circumstances relating to Your Demonstration of the Defendant Product at APEC 2019, including which Persons or Entities were permitted to personally view, handle, or otherwise inspect the Defendant Product demonstrated at APEC 2019, and identify all agreements entered into with those Persons or Entities before they were permitted to personally view, handle, or otherwise inspect the Defendant Product.

RESPONSE TO INTERROGATORY NO. 9 (DATED FEB. 18, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant objects to this Interrogatory to the extent it seeks information protected from disclosure by the attorney-client privilege, work product immunity, common interest, or any other applicable privilege or protection. Defendant objects to this Interrogatory because it seeks information that is outside the scope of this litigation. Defendant objects to this Interrogatory to the extent the documents or information requested are publicly available and/or equally available to the requesting party. Defendant objects to this Interrogatory to the extent the documents or information requested are not in Defendant's possession, custody, and/or control. Defendant further objects to this Interrogatory to the extent it requests customer and/or sampler information

that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent it seeks disputed legal and factual contentions, and testimony such as Invalidity Contentions, claim constructions, and other such reports identified by the Scheduling Order; Defendant will disclose its expert's opinions, Invalidity Contentions, claim constructions, and other such documents at the appropriate time as set by the Discovery and Scheduling Order, D.I. 69. Defendant further objects to this Interrogatory to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion.

Subject to and without waiving its objections, Defendant responds as follows: Defendant's investigation is ongoing and Defendant incorporates by reference its Initial

Disclosures pursuant to Rule 26. In addition, and pursuant to Federal Rule of Civil Procedure 33(d), Defendant will produce non-privileged documents located after a reasonably diligent search from which additional information responsive to the non-objectionable scope of this interrogatory can be derived.

Defendant's investigation is ongoing. Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 9 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Feb. 18, 2021, Defendant responds as follows:

MPS identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 10

For each MPS Defendant Product Component, describe where, by which Persons or Entities, and over what period it was manufactured, used, sold, offered for sale, and/or imported into the United States, and identify all supporting Documents and Persons most knowledgeable about the subject matter of Your response.

RESPONSE TO INTERROGATORY NO. 10 (DATED FEB. 18, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein Defendant further objects to the phrase "all" supporting Documents and Persons as overly broad, unduly burdensome, not reasonably calculated to lead to the discovery of admissible evidence, and not proportional to the needs of this litigation. Defendant objects to the phrases "most knowledgeable", and "subject matter of Your response" as vague and ambiguous. Defendant objects to this Interrogatory as overly broad and unduly burdensome on the ground that it is unbounded in time. Defendant objects to the phrase "offered for sale" as vague and ambiguous and to the extent that it calls for a legal conclusion. Defendant further objects to this Interrogatory to the extent it seeks information or documents protected from disclosure by attorney-client privilege, patent agent privilege, work product doctrine, or any other applicable privilege or protection from discovery. Defendant further objects to this Interrogatory to the extent it prematurely seeks disputed legal and factual contentions, and testimony such as Invalidity Contentions, claim constructions, and other such reports identified by the Scheduling Order; Defendant will disclose its expert's opinions, Invalidity Contentions, claim constructions, and other such documents at the appropriate time as set by the Discovery and Scheduling Order, D.I. 69. Defendant further objects to this Interrogatory to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant further objects to this Interrogatory to the extent it seeks information not in Defendant's possession, custody, or control. Defendant objects to this

Interrogatory to the extent it seeks information that is publicly available and/or equally available to the requesting party. Defendant objects to this Interrogatory to the extent it requests customer and/or sampler information that is not relevant or proportional to the needs of this case.

Subject to and without waiving its objections, Defendant responds as follows

[redacted]

[redacted]

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 10 (DATED AUG. 31, 2021)

MPS continues to object to the definition of "MPS Defendant Product Component" to include any product or MPS components used in products not made by MPS in this case, including the NVIDIA 48V-1V Power Solution and any MPS components used within the NVIDIA Power

Solution. Subject to this objection and MPS's previous objections presented on Feb. 18, 2021, Defendant responds as follows

[redacted]

[redacted]

<u>SECOND SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 10 (DATED SEP. 3, 2021):</u>

Subject to and without waiving its prior objections raised on Aug. 31, 2021 and Feb. 18, 2021, Defendant responds as follows:

[redacted]

[redacted]

[redacted]

THIRD SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 10 (DATED SEPT. 7, 2021)

Subject to and without waiving its prior objections raised on Feb. 18, 2021; Aug. 31, 2021; or Sept. 2, 2021, Defendant responds as follows:

Defendant incorporates by reference within its response to this interrogatory the relevant information included in its upcoming noninfringement, invalidity, and damages expert reports. Defendant will disclose its expert reports at the appropriate time as set by the Discovery and Scheduling Order, D.I. 69 and any modifications thereto by the parties.

Defendant further identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 11

For each MPS Defendant Product Component, provide shipping and financial information relating to each MPS Defendant Product Component, including on a monthly basis (for both the United States and worldwide), sales volume (i.e., quantity of units sold), revenue, costs of goods sold, other fixed or variable costs, and gross and net profits, and identify all supporting Documents and Persons most knowledgeable about the subject matter of Your response.

RESPONSE TO INTERROGATORY NO. 11 (DATED FEB. 18, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant further objects to the phrase "all" supporting Documents and Persons as overly broad, unduly burdensome, not reasonably calculated to lead to the discovery of admissible evidence, and not proportional to the needs of this litigation. Defendant objects to the phrases

"most knowledgeable", "sales volume," "revenue," and "subject matter of Your response" as vague and ambiguous. Defendant objects to the phrase "relating to" as indefinite, vague, ambiguous, overly broad, and unduly burdensome to the extent it seeks the production of information that is not relevant to any claim or defense of any party in this litigation or is not proportional to the needs of this litigation. Defendant objects to this Interrogatory as overly broad, unduly burdensome, and not proportional to the needs of this litigation to the extent it seeks financial information for each Defendant Product that is made, used, sold, or offered for sale by MPS outside the United States. Defendant objects to this Interrogatory as overly broad and unduly burdensome on the ground that it is unbounded in time. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant further objects to this Interrogatory to the extent it seeks information or documents protected from disclosure by attorney-client privilege, patent agent privilege, work product doctrine, or any other applicable privilege or protection from discovery. Defendant further objects to this Interrogatory to the extent it prematurely seeks disputed legal and factual contentions, and testimony such as Invalidity Contentions, claim constructions, and other such reports identified by the Scheduling Order; Defendant will disclose its expert's opinions, Invalidity Contentions, claim constructions, and other such documents at the appropriate time as set by the Discovery and Scheduling Order, D.I. 69. Defendant further objects to this Interrogatory to the extent it seeks information not in Defendant's possession, custody, or control. Defendant further objects to this Request to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it seeks information of third parties that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent it seeks information that is publicly available and/or equally available to the requesting party.

Subject to and without waiving its objections, Defendant responds as follows

[redacted]

[redacted]

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 11 (DATED AUG. 31, 2021)

MPS continues to object to the definition of "MPS Defendant Product Component" to include any product or MPS components used in products not made by MPS in this case, including the NVIDIA 48V-1V Power Solution and any MPS components used within the NVIDIA Power Solution. Subject to this objection and MPS's previous objections presented on Feb. 18, 2021, Defendant responds as follows

[redacted].

To the extent that Volterra alleges that the NVIDIA Power Solution and the components made by MPS used within the NVIDIA Power Solution are included in the definition of "MPS Defendant Product,"

[redacted]

Subject to the above objections and explanations, MPS discloses the following sales made entirely outside of the United States

[redacted]

[redacted]

[redacted]

SECOND SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 11 (DATED SEPT. 3, 2021)

Subject to and without waiving its previous objections raised on Aug. 31, 2021 and Feb. 18, 2021, Defendant responds as follows:

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

<u>THIRD SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 11 (DATED SEPT. 7, 2021)</u>

Subject to and without waiving its previous objections raised on Feb. 18, 2021; Aug. 31, 2021; and Sept. 2, 2021, Defendant responds as follows:

[redacted]

[redacted] [redacted]

[redacted] [redacted]

Defendant further identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 12

Identify all opinions or studies of which You are aware relating to infringement or validity of any claim of any Asserted Patent, including but not limited to the non-infringement opinion referenced in Your response to Interrogatory No. 3, and identify all persons who reliedon each such opinions or studies.

RESPONSE TO INTERROGATORY NO. 12 (DATED MAY 24, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant objects to the phrases "all" opinions or studies as overly broad, unduly burdensome, not reasonably calculated to lead to the discovery of admissible evidence, and not proportional to the needs of this litigation. Defendant objects to this Interrogatory to the extent it seeks information protected from disclosure by the attorney-client privilege, work product immunity, common interest, or any other applicable privilege or protection. Defendant further objects to this Interrogatory to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant objects to this Interrogatory to the extent the Interrogatory is unbounded in time. Defendant objects to this Interrogatory to the extent the documents or information requested are publicly available and/or equally available to the requesting party. Defendant further objects to this Interrogatory to the extent it requests customer and/or sampler information that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent the documents or information requested are not in Defendant's possession, custody, and/or control. Defendant objects to this Interrogatory to the extent it seeks disputed legal and factual contentions, and testimony such as Invalidity Contentions, claim constructions, and other such reports identified by the Scheduling Order; Defendant will disclose its expert's opinions, Invalidity Contentions, claim constructions, and other such documents at the appropriate time as set by the Discovery and Scheduling Order, D.I. 69. Defendant also objects to this Interrogatory as

encompassing multiple subparts, which pursuant to the District of Delaware Civil Local Rule 26.1(a), count towards Plaintiffs' discovery limits as set forth in Fed. R. Civ. P. 33(a)(1).

Subject to and without waiving its objections, Defendant responds as follows:

[redacted]

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 12 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on May 24, 2021, Defendant responds as follows:

MPS identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 13

For each Defendant Product identified in response to Interrogatory No. 1, and for each claim of each Asserted Patent, describe in complete detail the factual and legal basis and supporting evidence for Your contention, if any, that You did not possess the requisite intent or state of mind to contribute to or induce infringement of the claim.

RESPONSE TO INTERROGATORY NO. 13 (DATED MAY 24, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant further objects to this Interrogatory to the extent it seeks information protected from disclosure by the attorney-client privilege, work product immunity, common interest, or any other applicable privilege or protection. Defendant objects to this Interrogatory because it seeks information that is outside the scope of this litigation. Defendant further objects to this Interrogatory to the extent it requests customer and/or sampler information that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent the documents or information requested are publicly available and/or equally available to the requesting party. Defendant objects to this Interrogatory to the extent the documents or information requested are not in Defendant's possession, custody, and/or control. Defendant further objects to this Interrogatory to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant also objects to this Interrogatory as encompassing multiple subparts, which pursuant to the District of Delaware Civil Local Rule 26.1(a), count towards Plaintiffs' discovery limits as set forth in Fed. R. Civ. P. 33(a)(1).

Subject to and without waiving its objections, Defendant responds as follows:

[redacted].

In addition, this current Third Set of Interrogatories defines the "Defendant Product" as the 48V-1V Power Solution for CPU, SoC or ASIC Controller that Defendant demonstrated at the 2019 IEEE Applied Power Electronics Conference and Exposition ("APEC 2019") in Anaheim, CA and other Defendant products that are substantially similar to the 48V-1V Power Solution for CPU, SoC or ASIC Controller. As MPS has continued to disclose to Volterra, the Defendant Product as defined has never been sold either by MPS or by a third party, and thus MPS could not have contributed nor induced infringement on Volterra's asserted patents.

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 13 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on May 24, 2021, Defendant responds as follows:

MPS identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

SECOND SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 13 (DATED SEPT. 23, 2021)

[redacted]

[redacted]

[redacted]

[redacted]

<u>THIRD SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 13 (DATED OCT. 7, 2021)</u>

Subject to and without waiving its previous objections raised on May 24, 2021, Sept. 7, 2021, and Sept. 23, 2021, Defendant responds as follows:

[redacted]

[redacted]

MPS incorporates by reference the relevant positions in its upcoming expert reports and deposition testimony, which will set forth more fully the basis of MPS's above-stated contentions.

INTERROGATORY NO. 14

For each Defendant Product identified in response to Interrogatory No. 1 and for the Nvidia Accused Product, and for each claim of each Asserted Patent, describe in complete detail the factual and legal basis and supporting evidence for Your contention, if any, that the product does not infringe the claim, including the identity of each claim limitation allegedly missing from each such product.

RESPONSE TO INTERROGATORY NO. 14 (DATED. AUG. 2, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant further objects to each Definition, Instruction, and Interrogatory that uses the term "Nvidia Accused Product" as outside the scope of this litigation to the extent is seeks discovery of any Defendant product that does not fall under the scope of "Accused Products" as defined at Paragraph 18 of Volterra's Second Amended Complaint ("SAC"), D.I. 71. Defendant objects to this Interrogatory to the extent it seeks information protected from disclosure by the attorney-client privilege, work product immunity, common interest, or any other applicable privilege or protection. Defendant further objects to this Interrogatory to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant also objects to this Interrogatory as consisting of multiple subparts which pursuant to the District of Delaware Civil Local Rule 26.1(a), count towards Plaintiffs' discovery limits as set forth in Fed. R. Civ. P. 33(a)(1).

Subject to and without waiving its objections, Defendant responds as follows

At least the following claim elements in the Asserted Patents are not present in the MPS Power Solution

[redacted]

[redacted]

[redacted]

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 14 (DATED AUG. 31, 2021)

Subject to and without waiving its previous objections presented on Aug. 31, 2021, MPS supplements its responses as follows:

In addition to the prior elements presented above, at least the following claim elements in the Asserted Patents are not present in the MPS Power Solution. MPS notes that the elements described above and below are exemplary only and not limiting.

[redacted]

[redacted]

[redacted]

[redacted]

SECOND SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 14 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Aug. 02, 2021 or Aug. 31, 2021, Defendant responds as follows:

Defendant incorporates by reference within its response to this interrogatory the relevant noninfringement positions included in its upcoming expert reports. Defendant will disclose its expert reports at the appropriate time as set by the Discovery and Scheduling Order, D.I. 69 and any modifications thereto by the parties.

Defendant further identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

THIRD SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 14 (DATED SEPT. 23, 2021)

Subject to and without waiving its previous objections raised on Aug. 2, 2021, Aug. 31, 2021, or Sept. 7, 2021, Defendant responds as follows:

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

MPS incorporates by reference its upcoming expert reports, which will set forth more fully the basis of MPS's above-stated non-infringement contentions.

FOURTH SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 14 (DATED OCT. 7, 2021)

Subject to and without waiving its previous objections raised on Aug. 2, 2021, Aug. 31, 2021, Sept. 7, 2021, or Sept. 23, 2021, Defendant responds as follows:

[redacted]

MPS incorporates by reference the relevant positions in its upcoming expert reports and deposition testimony, which will set forth more fully the basis of MPS's above-stated non-infringement contentions.

INTERROGATORY NO. 15

Describe in complete detail the factual and legal basis and supporting evidence for Your contention, if any, that any Asserted Patent is unenforceable.

RESPONSE TO INTERROGATORY NO. 15 (DATED AUG. 2, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant further objects to this Interrogatory to the extent it seeks information protected from disclosure by the attorney-client privilege, work product immunity, common interest, or any other applicable privilege or protection. Defendant objects to this Interrogatory to the extent it seeks information that is outside the scope of this litigation. Defendant objects to this Interrogatory to the extent the documents or information requested are publicly available and/or equally available to the requesting party. Defendant further objects to each Definition, Instruction, and Interrogatory that uses the term "Nvidia Accused Product" as outside the scope of this litigation to the extent is seeks discovery of any Defendant product that does not fall under the

scope of "Accused Products" as defined at Paragraph 18 of Volterra's Second Amended Complaint ("SAC"), D.I. 71. Defendant further objects to this Interrogatory to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant also objects to this Interrogatory as encompassing multiple subparts, which pursuant to the District of Delaware Civil Local Rule 26.1(a), count towards Plaintiffs' discovery limits as set forth in Fed. R. Civ. P. 33(a)(1).

Subject to and without waiving its objections, Defendant responds as follows:

MPS directs Volterra to the arguments presented in its Invalidity Contentions, which were served on December 1, 2020.

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 15 (DATED AUG. 31, 2021)

Subject to and without waiving its objections, Defendant responds as follows:

MPS would like to clarify that its previous response directing Volterra to the arguments presented in its Invalidity Contentions covers both why Volterra's patents are unenforceable as well as why Volterra's patents are invalid.

SECOND SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 15 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Aug. 02, 2021 or Aug. 31, 2021, Defendant responds as follows:

Defendant incorporates by reference within its response to this interrogatory the relevant unenforceability and invalidity positions included in its upcoming expert reports. Defendant will

disclose its expert reports at the appropriate time as set by the Discovery and Scheduling Order, D.I. 69 and any modifications thereto by the parties.

Defendant further identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory

INTERROGATORY NO. 16

Describe in complete detail the factual and legal basis and supporting evidence for any and all affirmative defenses that You intend to assert in this case.

RESPONSE TO INTERROGATORY NO. 16 (DATED AUG. 2, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant objects to this Interrogatory to the extent it seeks information protected from disclosure by the attorney-client privilege, work product immunity, common interest, or any other applicable privilege or protection. Defendant objects to this Interrogatory because it seeks information that is outside the scope of this litigation. Defendant objects to this Interrogatory to the extent the documents or information requested are publicly available and/or equally available to the requesting party. Defendant further objects to this Interrogatory to the extent it requests customer and/or sampler information that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent it seeks disputed legal and factual contentions. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion.

Subject to and without waiving its objections, Defendant responds as follows:

MPS directs Volterra to its arguments regarding Volterra's lack of evidence to support its direct and indirect infringement allegations as presented in MPS's Opening Brief (D.I. 84) and Reply Brief (D.I. 95) in support of its Motion to Dismiss Volterra's Second Amended Complaint. MPS further directs Volterra to the arguments presented in its Invalidity Contentions, which were served on December 1, 2020.

Defendant's investigation is ongoing. Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

<u>FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 16 (DATED AUG. 31, 2021)</u>

Subject to and without waiving its previous objections raised on Aug. 02, 2021, Defendant responds as follows:

In addition to the arguments highlighted in MPS's previous response, MPS notes that as MPS's motion to dismiss is still pending before the Court and because MPS has not yet filed its answer in this case, any interrogatory directed towards MPS's affirmative defenses is premature. MPS will disclose its affirmative defenses at the appropriate time in this case.

<u>SECOND SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 16 (DATED SEPT. 7, 2021)</u>

Subject to and without waiving its previous objections raised on Aug. 02, 2021 or Aug. 31, 2021, Defendant responds as follows:

Defendant incorporates by reference within its response to this interrogatory the relevant positions included in its upcoming expert reports. Defendant will disclose its expert reports at the appropriate time as set by the Discovery and Scheduling Order, D.I. 69 and any modifications thereto by the parties.

Defendant further identifies that it intends to rely upon at least the following affirmative defenses:

[redacted] [redacted]

[redacted]

- The Asserted Patents are not infringed by MPS. Defendant incorporates by reference within its response to this interrogatory the relevant non-infringement positions included in its upcoming expert reports.
- The Asserted Patents are invalid. Defendant incorporates by reference within its response to this interrogatory the relevant invalidity positions included in its upcoming expert reports.
- Volterra is barred, based on statements, representations, and admissions made during prosecution of the patent applications resulting in the Asserted Patents or related patent applications, from asserting any interpretation of any valid, enforceable claim of the Asserted Patents that would be broad enough to cover any Accused Product alleged to infringe the Asserted Patents, either literally or under the doctrine of equivalents.
- Volterra is barred by one or more of the equitable doctrines, such as estoppel, acquiescence, waiver, and unclean hands.
- Volterra's claims for damages are statutorily limited or barred by 35 U.S.C. §§ 286 and/or 287.
- Volterra is barred under 35 U.S.C. § 288 from recovering costs associated with its action.

- Volterra is not entitled to injunctive relief as it has, at a minimum, an adequate remedy at law upon any finding of infringement and has not suffered any irreparable injury.
- Volterra is barred from obtaining a finding of willfulness or receiving enhanced damages because it has not alleged that MPS engaged in reprehensible conduct, and MPS has engaged in no such conduct, which is a prerequisite for a willfulness finding and an award of enhanced damages.
- The Second Amended Complaint fails to state a claim upon which relief can be granted, for at least the reasons described in MPS's Motion to Dismiss the SAC filed in this action (D.I. 83).

Defendant further identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

THIRD SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 16 (DATED SEPT. 23, 2021)

Subject to and without waiving its previous objections raised on Aug. 2, 2021, Aug. 31, 2021, or Sept. 7, 2021, Defendant additionally responds as follows:

- Defendant incorporates by reference all of its responses to Interrogatory Nos. 13 and 14.
- [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted] [redacted]

[redacted]

[redacted]

[redacted]

Defendant further identifies the forthcoming deposition testimony of third-parties in this case, including but not limited to named inventor Angel Gentchev, as further containing relevant information to this interrogatory. Defendant incorporates by reference the relevant positions included in its upcoming expert reports. Defendant incorporates by reference the relevant positions included in its forthcoming Answer to the operative second amended complaint once the Court rules on the pending motion to dismiss the second amended complaint (D.I. 84).

INTERROGATORY NO. 17:

For each Defendant Product identified in response to Interrogatory No. 1 and for the Nvidia Accused Product, identify and describe in complete detail the role of each entity involved in the manufacture, assembly, distribution, sale, offer for sale, or importation of the product from the manufacturer to the end user.

RESPONSE TO INTERROGATORY NO. 17 (DATED AUG. 2, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant further objects to this Interrogatory to the extent it seeks information or documents protected from disclosure by attorney-client privilege, patent agent privilege, work product doctrine, or any other applicable privilege or protection from discovery. Defendant further objects to this Interrogatory to the extent it prematurely seeks disputed legal and factual contentions, and testimony. Defendant further objects to this Interrogatory to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant further objects to this Interrogatory to the extent it seeks information not in Defendant's possession, custody, or control.

Defendant objects to this Interrogatory to the extent it seeks information that is publicly available and/or equally available to the requesting party. Defendant objects to this Interrogatory to the extent it requests customer and/or sampler information that is not relevant or proportional to the needs of this case.

Subject to and without waiving its objections, Defendant responds as follows:

[redacted]

As MPS does not make the NVIDIA Accused Product, MPS does not have the prerequisite knowledge to answer this Interrogatory with regard to the NVIDIA Accused Product.

<u>FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 17 (DATED SEPT. 7, 2021)</u>

Subject to and without waiving its previous objections raised on Aug. 02, 2021, Defendant responds as follows:

[redacted]

[redacted].

Defendant further identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 18

Identify and describe in complete detail the costs (e.g., exhibit fees, development costs, component costs) and benefits (e.g., contracts or agreements discussed, contracts or agreements entered into, pitch opportunities, goodwill) associated with Your demonstration of the 48V-1V Power Solution at APEC 2019.

RESPONSE TO INTERROGATORY NO. 18 (DATED AUG. 2, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant objects to the phrases "costs and benefits," and "goodwill" as vague and ambiguous, overly broad, and unduly burdensome to the extent it seeks information that is not relevant to any claim or defense of any party in this litigation or is not proportional to the needs of this litigation. Defendant objects to this Interrogatory as overly broad and unduly burdensome on the ground that it is unbounded in time. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant further objects to this Interrogatory to the extent it seeks information or documents protected from disclosure by attorney-client privilege, patent agent privilege, work product doctrine, or any other applicable privilege or protection from discovery. Defendant further objects to this Request to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it seeks information of third parties that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent it seeks information that is publicly available and/or equally available to the requesting party.

Subject to and without waiving its objections, Defendant responds as follows:

[redacted]

[redacted]

[redacted]

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 18 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Aug. 02, 2021, Defendant responds as follows:

MPS identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 19

Identify and describe in complete detail all potential and actual customers, including customers of MPS Defendant Product Components, that expressed interest in MPS or its products based on Your demonstration of the 48V-1V Power Solution at APEC 2019.

RESPONSE TO INTERROGATORY NO. 19 (DATED AUG. 2, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant objects to this Interrogatory as vague, ambiguous, overly broad, and unduly burdensome to the extent it seeks information that is not relevant to any claim or defense of any party in this litigation or is not proportional to the needs of this litigation. Defendant objects to this Interrogatory as overly broad and unduly burdensome on the ground that it is unbounded in time. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant further objects to this Interrogatory to the extent it seeks information or documents protected from disclosure by attorney-client privilege, patent agent privilege, work product doctrine, or any other

applicable privilege or protection from discovery. Defendant further objects to this Request to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it seeks information of third parties that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent it seeks information that is publicly available and/or equally available to the requesting party.

Subject to and without waiving its objections, Defendant responds as follows

[redacted]

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 19 (DATED AUG. 31, 2021)

Subject to and without waiving its previous objections presented on Aug. 02, 2021, Defendant responds as follows

[redacted]

SECOND SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 19 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Aug. 02, 2021, Defendant responds as follows:

MPS identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 20

Describe in complete detail the process of pitching Nvidia regarding the development of the Nvidia Accused Product and securing the design win, including [redacted] Your pitches, presentations, and proposals that You provided to Nvidia regarding the Nvidia Accused Product; and any selection or confirmation Communications or Documents You received from Nvidia, including any purchase orders, invoices, contracts, or agreements regarding the Nvidia Accused Product or regarding any components You provided to be used in the Nvidia Accused Product.

RESPONSE TO INTERROGATORY NO. 20 (DATED AUG. 2, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant objects to this Interrogatory as vague, ambiguous, overly broad, and unduly burdensome to the extent it seeks information that is not relevant to any claim or defense of any party in this litigation or is not proportional to the needs of this litigation. Defendant objects to this Interrogatory as overly broad and unduly burdensome on the ground that it is unbounded in time. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant further objects to this Interrogatory to the extent it seeks information or documents protected from disclosure by attorney-client privilege, patent agent privilege, work product doctrine, or any other applicable privilege or protection from discovery. Defendant further objects to this Request to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it seeks information of third parties that is not relevant or

proportional to the needs of this case. Defendant objects to this Interrogatory to the extent it seeks information that is publicly available and/or equally available to the requesting party.

Subject to and without waiving its objections, Defendant responds as follows:

[redacted].

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced

FIRST SUPPLEMENTARY RESPONSE TO INTERROGATORY 20 (DATED AUG. 31, 2021)

Subject to and without waiving its previous objections raised on Aug. 02, 2021, Defendant responds as follows:

[redacted]

SECOND SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 20 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Aug. 02, 2021, Defendant responds as follows:

MPS identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 21

Identify and describe in complete detail all requests for technical support or assistance You received and all technical support or assistance You provided regarding the Nvidia Accused Product or regarding the Nvidia Accused Product's components, including any reports of problems, configuration questions or issues, defective boards or components identified or returned, Entities communicating such requests or receiving such technical support or assistance, and locations from which You provided such technical support or assistance.

RESPONSE TO INTERROGATORY NO. 21 (DATED AUG. 2, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant objects to this Interrogatory as vague, ambiguous, overly broad, and unduly burdensome to the extent it seeks information that is not relevant to any claim or defense of any party in this litigation or is not proportional to the needs of this litigation. Defendant objects to this Interrogatory as overly broad and unduly burdensome on the ground that it is unbounded in time. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant further objects to this Interrogatory to the extent it seeks information or documents protected from disclosure by attorney-client privilege, patent agent privilege, work product doctrine, or any other applicable privilege or protection from discovery. Defendant further objects to this Request to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it seeks information of third parties that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent it seeks information that is publicly available and/or equally available to the requesting party.

Subject to and without waiving its objections, Defendant responds as follows:

[redacted]

[redacted]

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 21 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Aug. 02, 2021, Defendant responds as follows:

MPS identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 22

Identify and describe in complete detail all pitches, presentations, and proposals that You provided to [redacted] that include at least one coupled inductor, including any response from [redacted] related to Your pitch, presentation, or proposal or Communications with [redacted] related to Volterra, Maxim, or the Asserted Patents.

RESPONSE TO INTERROGATORY NO. 22 (DATED AUG. 2, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant objects to this Interrogatory as vague, ambiguous, overly broad, and unduly burdensome to the extent it seeks information that is not relevant to any claim or defense of any party in this litigation or is not proportional to the needs of this litigation. Defendant objects to this Interrogatory as overly broad and unduly burdensome on the ground that it is unbounded in time. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant further objects to this Interrogatory to the extent it seeks information or documents protected from disclosure by attorney-client privilege, patent agent privilege, work product doctrine, or any other

applicable privilege or protection from discovery. Defendant further objects to this Request to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it seeks information of third parties that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent it seeks information that is publicly available and/or equally available to the requesting party.

Subject to and without waiving its objections, Defendant responds as follows:

[redacted]

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced.

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 22 (DATED AUG. 31, 2021)

Subject to and without waiving its previously raised objections on Aug. 02, 2021, Defendant responds as follows:

[redacted]

SECOND SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 22 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Aug. 02, 2021, Defendant responds as follows:

MPS identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 23

Identify and describe in complete detail all pitches, presentations, and proposals that You provided to any potential or actual customer that included at least one coupled inductor.

RESPONSE TO INTERROGATORY NO. 23 (AUG. 2, 2021):

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant objects to this Interrogatory as vague, ambiguous, overly broad, and unduly burdensome to the extent it seeks information that is not relevant to any claim or defense of any party in this litigation or is not proportional to the needs of this litigation. Defendant objects to this Interrogatory as overly broad and unduly burdensome on the ground that it is unbounded in time. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant further objects to this Interrogatory to the extent it seeks information or documents protected from disclosure by attorney-client privilege, patent agent privilege, work product doctrine, or any other applicable privilege or protection from discovery. Defendant further objects to this Request to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it seeks information of third parties that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent it seeks information that is publicly available and/or equally available to the requesting party.

Subject to and without waiving its objections, Defendant responds as follows:

[redacted]

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 23 (AUG. 31, 2021)

Subject to and without waiving its previously raised objections on Aug. 02, 2021, Defendant responds as follows:

[redacted]

SECOND SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 23 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Aug. 02, 2021, Defendant responds as follows:

MPS identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 24

Identify and describe in complete detail all design wins You secured with Nvidia before and after the Nvidia Accused Product design win.

RESPONSE TO INTERROGATORY NO. 24 (DATED AUG. 2, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant objects to this Interrogatory as vague, ambiguous, overly broad, and

unduly burdensome to the extent it seeks information that is not relevant to any claim or defense of any party in this litigation or is not proportional to the needs of this litigation. Defendant objects to this Interrogatory as overly broad and unduly burdensome on the ground that it is unbounded in time. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant further objects to this Interrogatory to the extent it seeks information or documents protected from disclosure by attorney-client privilege, patent agent privilege, work product doctrine, or any other applicable privilege or protection from discovery. Defendant further objects to this Request to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it seeks information of third parties that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent it seeks information that is publicly available and/or equally available to the requesting party.

Subject to and without waiving its objections, Defendant responds as follows:

[redacted]

As discovery is ongoing, MPS is investigating this issue and will supplement this response as more information becomes available. Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 24 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Aug. 02, 2021, Defendant responds as follows:

MPS identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 25

Describe in complete detail the purpose of Your Communications with Coupled Inductor Manufacturers that occurred after You secured the design win for the Nvidia Accused Product, including identification of the intended use of each coupled inductor referenced in the emails You produced between MPS and [redacted]

RESPONSE TO INTERROGATORY NO. 25 (DATED AUG. 2, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant objects to this Interrogatory as vague, ambiguous, overly broad, and unduly burdensome to the extent it seeks information that is not relevant to any claim or defense of any party in this litigation or is not proportional to the needs of this litigation. Defendant objects to this Interrogatory as overly broad and unduly burdensome on the ground that it is unbounded in time. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant further objects to this Interrogatory to the extent it seeks information or documents protected from disclosure by attorney-client privilege, patent agent privilege, work product doctrine, or any other applicable privilege or protection from discovery. Defendant further objects to this Request to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it seeks information of third parties that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent it seeks information that is publicly available and/or equally available to the requesting party.

Subject to and without waiving its objections, Defendant responds as follows:

[redacted]

[redacted]

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 25 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Aug. 02, 2021, Defendant responds as follows:

MPS identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 26

Identify and describe in complete detail Your retention policies since the beginning of 2018 for documents, emails, and electronic assemblies and components

RESPONSE TO INTERROGATORY NO. 26 (DATED AUG. 2, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant objects to this Interrogatory as vague, ambiguous, overly broad, and unduly burdensome to the extent it seeks information that is not relevant to any claim or defense of any party in this litigation or is not proportional to the needs of this litigation. Defendant objects to this Interrogatory as overly broad and unduly burdensome on the ground that it is unbounded in time. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant further objects to this Interrogatory to the extent it seeks information or documents protected from disclosure by attorney-client privilege, patent agent privilege, work product doctrine, or any other applicable privilege or protection from discovery. Defendant objects to this Interrogatory to the

extent it seeks information that is publicly available and/or equally available to the requesting party.

Subject to and without waiving its objections, Defendant responds as follows:

[redacted].

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 26 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Aug. 02, 2021, Defendant responds as follows:

MPS identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 27

[redacted]

RESPONSE TO INTERROGATORY NO. 27 (DATED AUG. 2, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant objects to this Interrogatory as vague, ambiguous, overly broad, and unduly burdensome to the extent it seeks information that is not relevant to any claim or defense of any party in this litigation or is not proportional to the needs of this litigation. Defendant objects to this Interrogatory as overly broad and unduly burdensome on the ground that it is unbounded in time. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant further objects to this Interrogatory to the extent it seeks information or documents protected from disclosure by attorney-client privilege, patent agent privilege, work product doctrine, or any other

applicable privilege or protection from discovery. Defendant further objects to this Request to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it seeks information of third parties that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent it seeks information that is publicly available and/or equally available to the requesting party.

Subject to and without waiving its objections, Defendant responds as follows:

[redacted]

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 27 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Aug. 02, 2021, Defendant responds as follows:

MPS identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

INTERROGATORY NO. 28

[redacted]

RESPONSE TO INTERROGATORY NO. 28 (DATED AUG. 2, 2021)

Defendant incorporates all of its objections and reservations of rights as if specifically alleged herein. Defendant objects to this Interrogatory as vague, ambiguous, overly broad, and unduly burdensome to the extent it seeks information that is not relevant to any claim or defense of any party in this litigation or is not proportional to the needs of this litigation. Defendant objects to this Interrogatory as overly broad and unduly burdensome on the ground that it is unbounded in time. Defendant objects to this Interrogatory to the extent it calls for a legal conclusion. Defendant further objects to this Interrogatory to the extent it seeks information or documents protected from disclosure by attorney-client privilege, patent agent privilege, work product doctrine, or any other applicable privilege or protection from discovery. Defendant further objects to this Request to the extent it seeks information which MPS is under a duty to third parties not to disclose. Defendant objects to this Interrogatory to the extent it seeks information of third parties that is not relevant or proportional to the needs of this case. Defendant objects to this Interrogatory to the extent it seeks information that is publicly available and/or equally available to the requesting party.

Subject to and without waiving its objections, Defendant responds as follows:

[redacted]

[redacted]

Defendant reserves the right to supplement and/or amend this response as further information becomes available, and/or after responsive, non-privileged documents are otherwise produced

FIRST SUPPLEMENTAL RESPONSE TO INTERROGATORY NO. 28 (DATED SEPT. 7, 2021)

Subject to and without waiving its previous objections raised on Aug. 02, 2021, Defendant responds as follows:

MPS identifies the deposition transcripts already taken and forthcoming in this case as further containing relevant information to this interrogatory.

/s/ Bob Steinberg
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Andrew E. Russell (No. 5382)
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Dated: October 7, 2021

CERTIFICATE OF SERVICE

I, Bob Steinberg, hereby certify that on October 7, 2021 this document was served on the persons listed below in the manner indicated

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Attorneys for Defendant

EXHIBIT 8

US006362986B1

(12) **United States Patent**
Schultz et al.

(10) **Patent No.: US 6,362,986 B1**
(45) **Date of Patent: Mar. 26, 2002**

(54) **VOLTAGE CONVERTER WITH COUPLED INDUCTIVE WINDINGS, AND ASSOCIATED METHODS**

(75) Inventors: **Aaron M. Schultz**, Sunnyvale, CA (US); **Charles R. Sullivan**, Hanover, NH (US)

(73) Assignee: **Volterra, Inc.**, Fremont, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/814,555**

(22) Filed: **Mar. 22, 2001**

(51) **Int. Cl.**[7] **H02M 7/5387**

(52) **U.S. Cl.** **363/132**

(58) **Field of Search** 363/16, 17, 56.01, 363/56.02, 97, 98, 131, 132

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,204,809 A 4/1993 Andresen
5,764,500 A * 6/1998 Matos 363/132
6,018,468 A * 1/2000 Archer et al. 363/17

OTHER PUBLICATIONS

"A Novel Modeling Concept for Multi–coupling Core Structures", Pit–Leong Wong, Fred C. Lee, Xiaochuan Jia and Daan van Wyk—Document prepared for the Center for Power Electronics Systems, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, Jan. 2001.

"Investigating Coupling Inductors in the Interleaving QSW VRW", Pit–Leong, Qiaoqiao Wu, Peng Xu, Bo Yang and Fred C. Lee, Document prepared for the Center for Power Electronics Systems, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, Mar. 2000.

* cited by examiner

Primary Examiner—Matthew Nguyen
(74) *Attorney, Agent, or Firm*—Curtis A. Vock, Esq.; Lathrop & Gage L.C.

(57) **ABSTRACT**

A DC-to-DC converter generates an output voltage from an input voltage. The converter includes first and second inductive windings and a magnetic core. One end of the first winding is switched at about 180 degrees out of phase with one end of the second winding, between ground and the input voltage. The first winding is wound about the core in a first orientation, and the second winding is also wound about the core in the first orientation so as to increase coupling between windings and to reduce ripple current in the windings and other parts of the circuit. This version is a buck converter—versions that form boost, buck-boost and other converters are also provided. The invention also provides a multi-phase DC-to-DC converter for providing an output voltage from an input voltage. The converter has N ($N \geqq 2$) inductive windings alternatively switched, again in the buck-converter version, between ground and the input voltage. Again, boost, buck-boost, or other versions are also provided. Each of the N windings has a turn-on switching transition separated in switching phase by at least about 360/N degrees from any other of the windings. Each of the windings also has a turn-off switching transition separated in phase by at least about 360/N degrees from any other of the windings. Each of the N windings is wound about the core in like orientation to increase coupling between windings and to reduce ripple current in the windings and other parts of the circuit. The invention also provides suitable core structures.

40 Claims, 16 Drawing Sheets

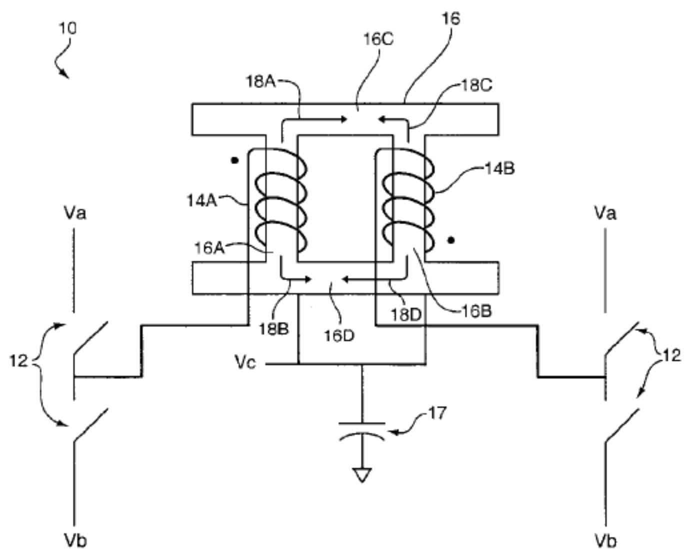


FIG. 1

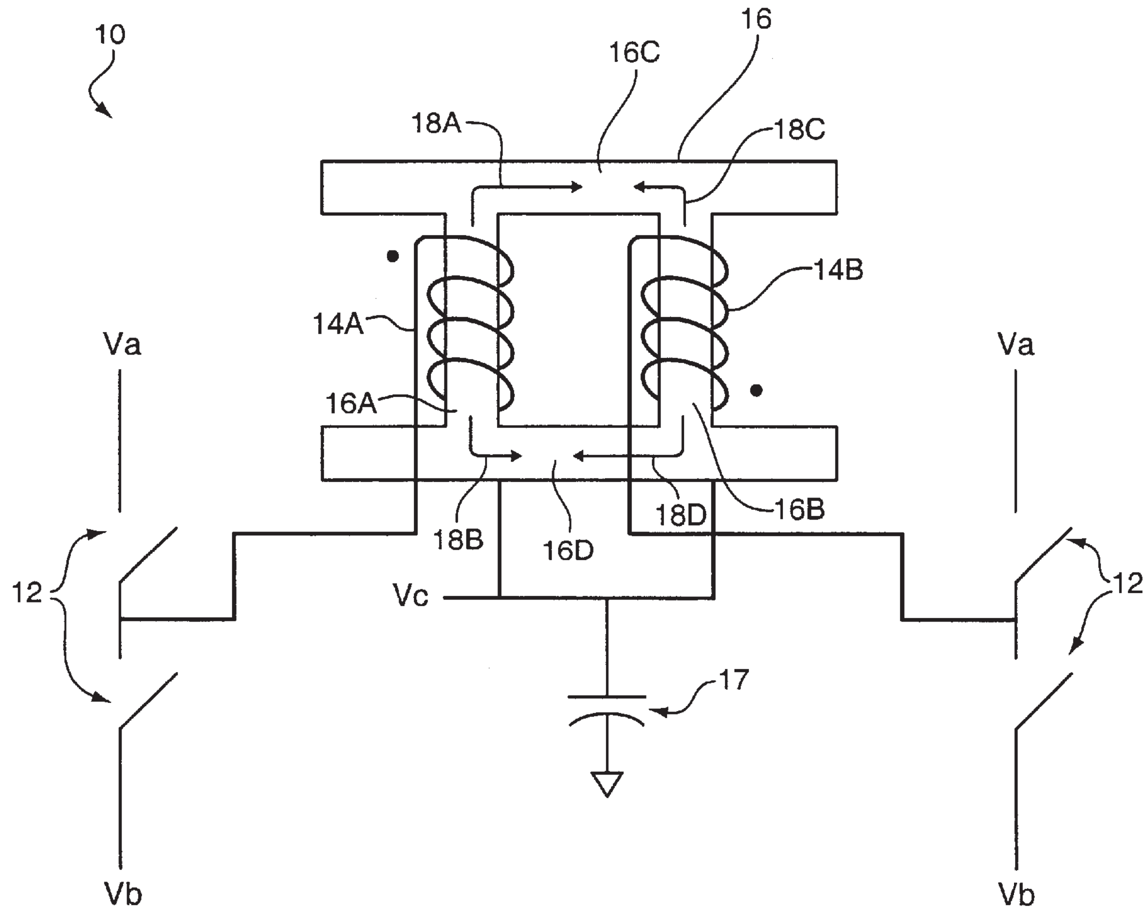

10
16
16C
18A
18C
14B
14A
Va
Va
16A
16B
18D
18B
16D
12
12
Vc
17
Vb
Vb

FIG. 2

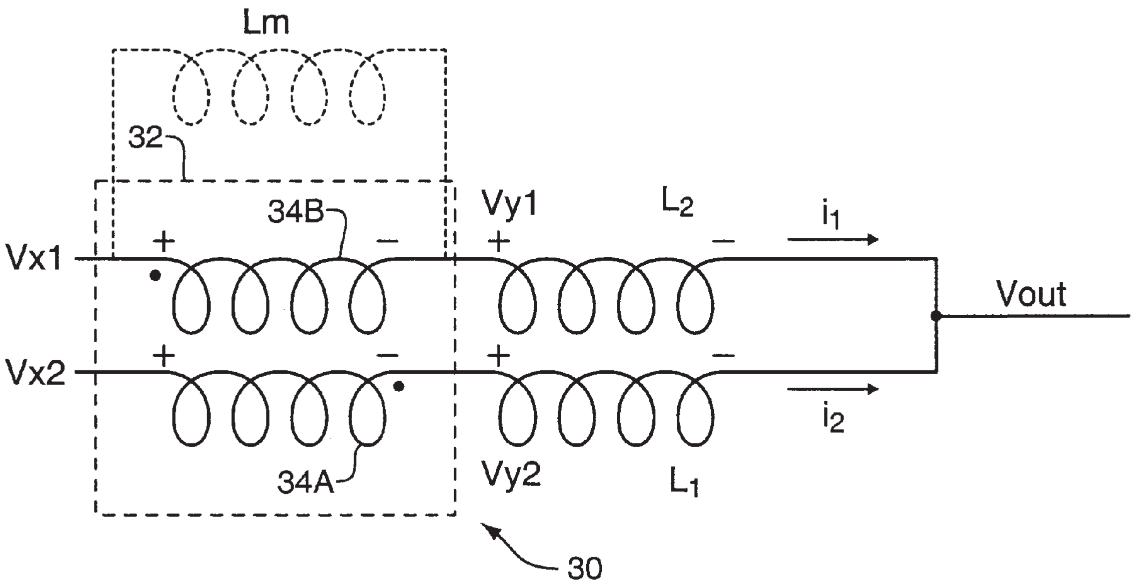


FIG. 3

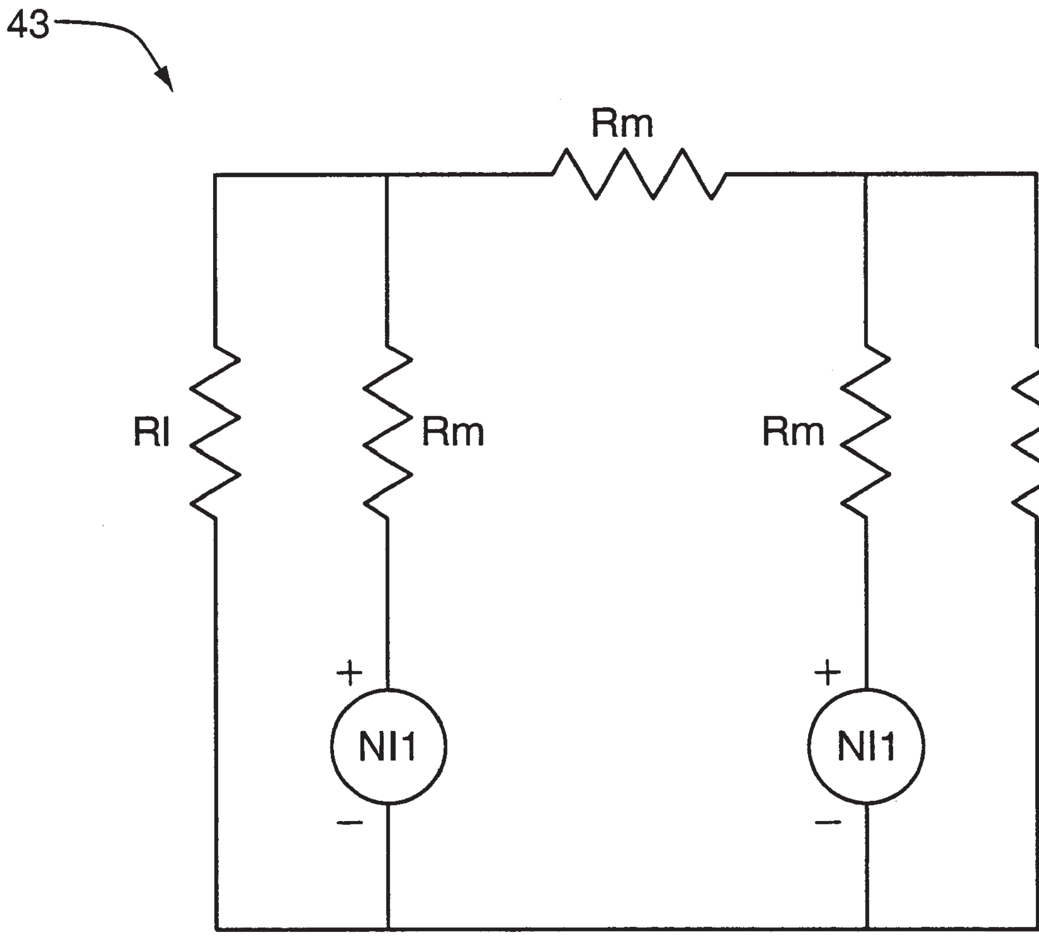


FIG. 3A

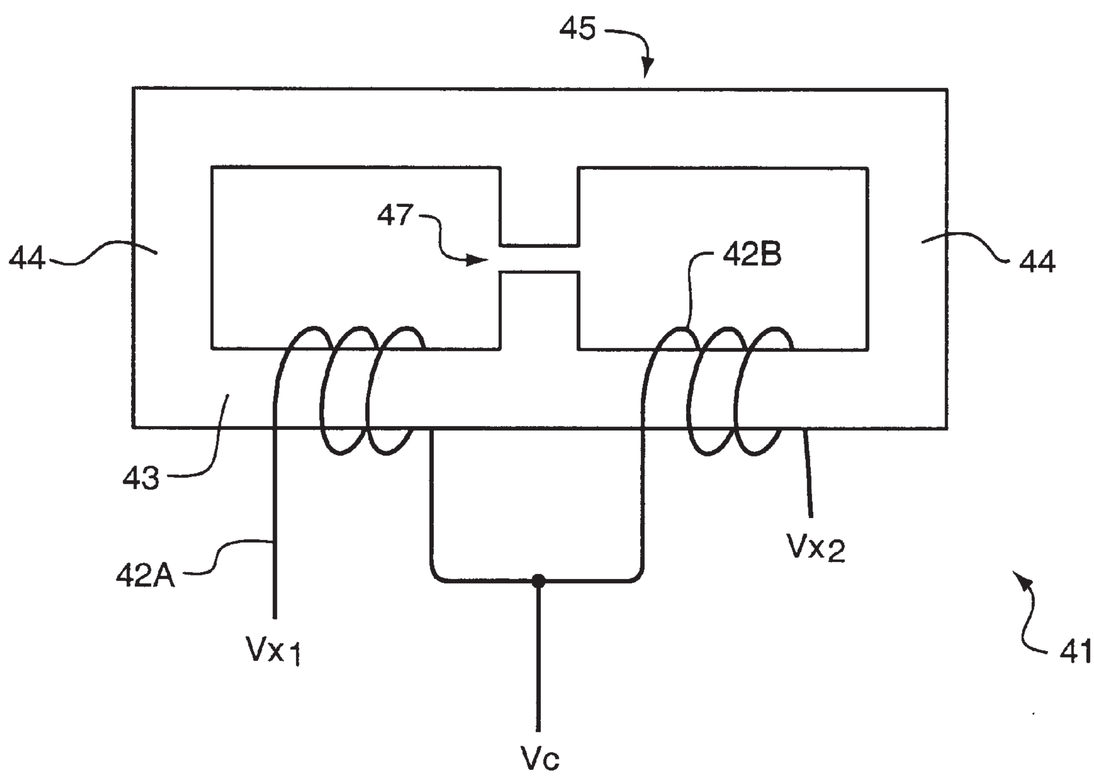
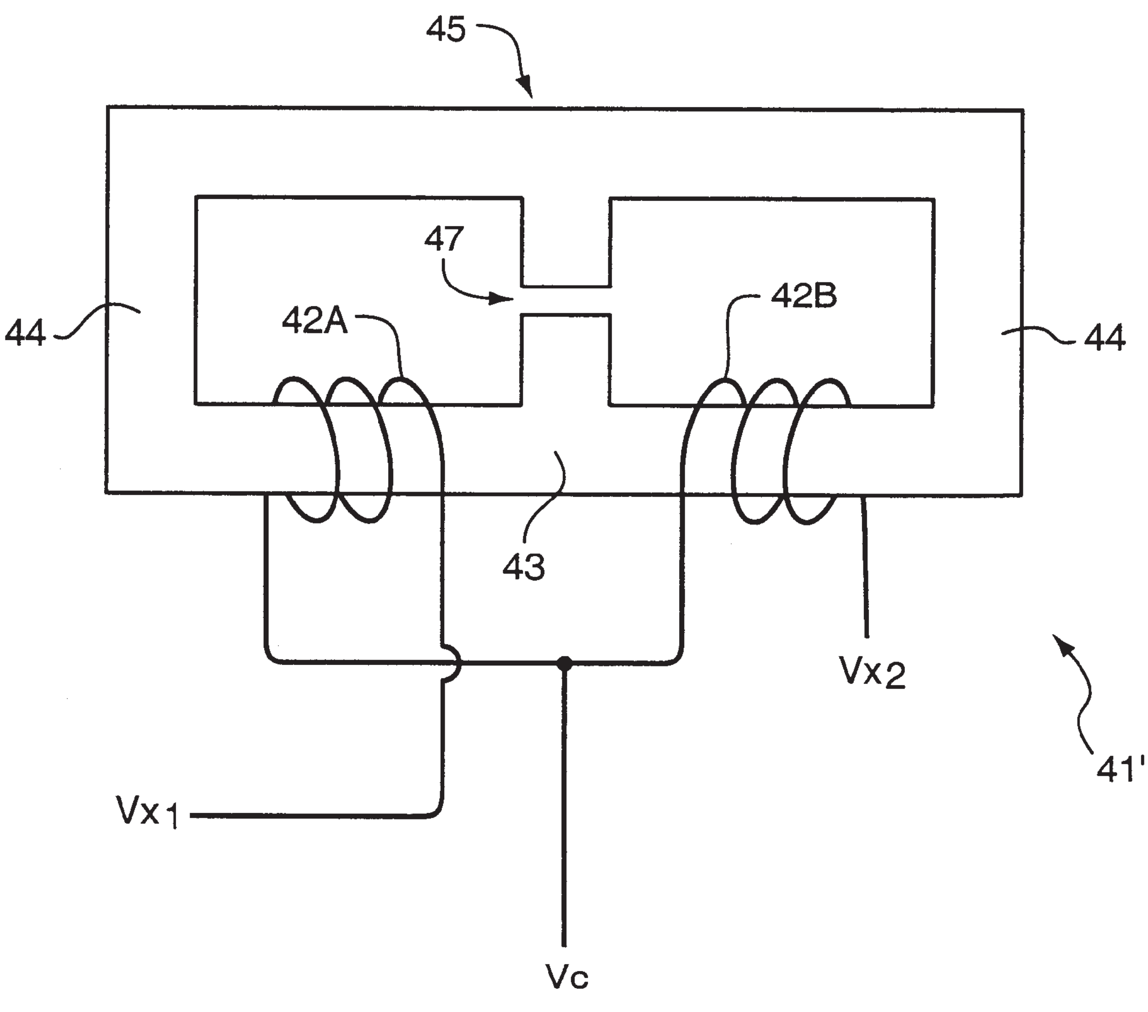


FIG. 3B



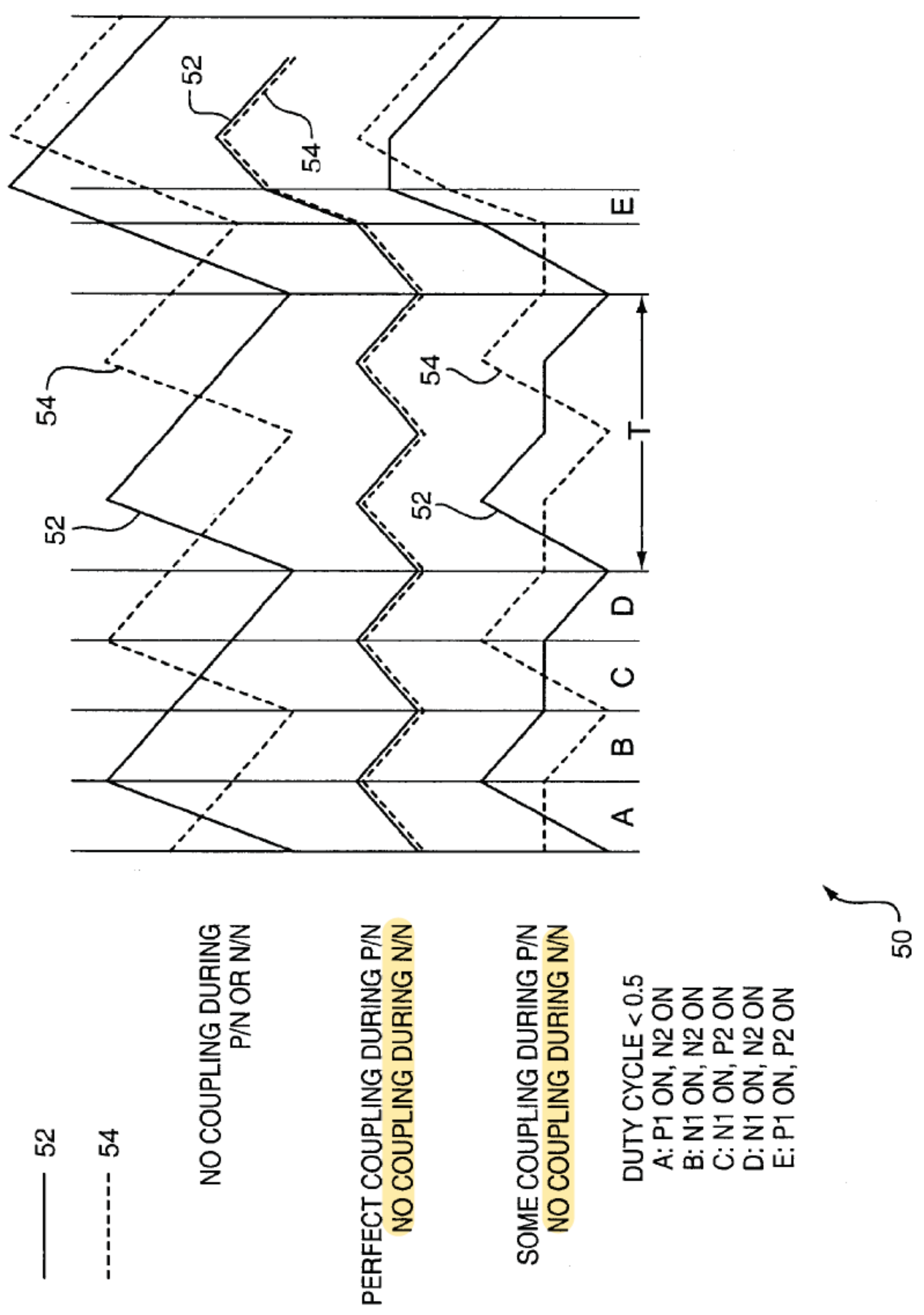

52
54
52
54
52
54
52
54
T
A
B
C
D
E
50
52
54
NO COUPLING DURING P/N OR N/N
PERFECT COUPLING DURING P/N
NO COUPLING DURING N/N
SOME COUPLING DURING P/N
NO COUPLING DURING N/N
DUTY CYCLE < 0.5
A: P1 ON, N2 ON
B: N1 ON, N2 ON
C: N1 ON, P2 ON
D: N1 ON, N2 ON
E: P1 ON, P2 ON

FIG. 4

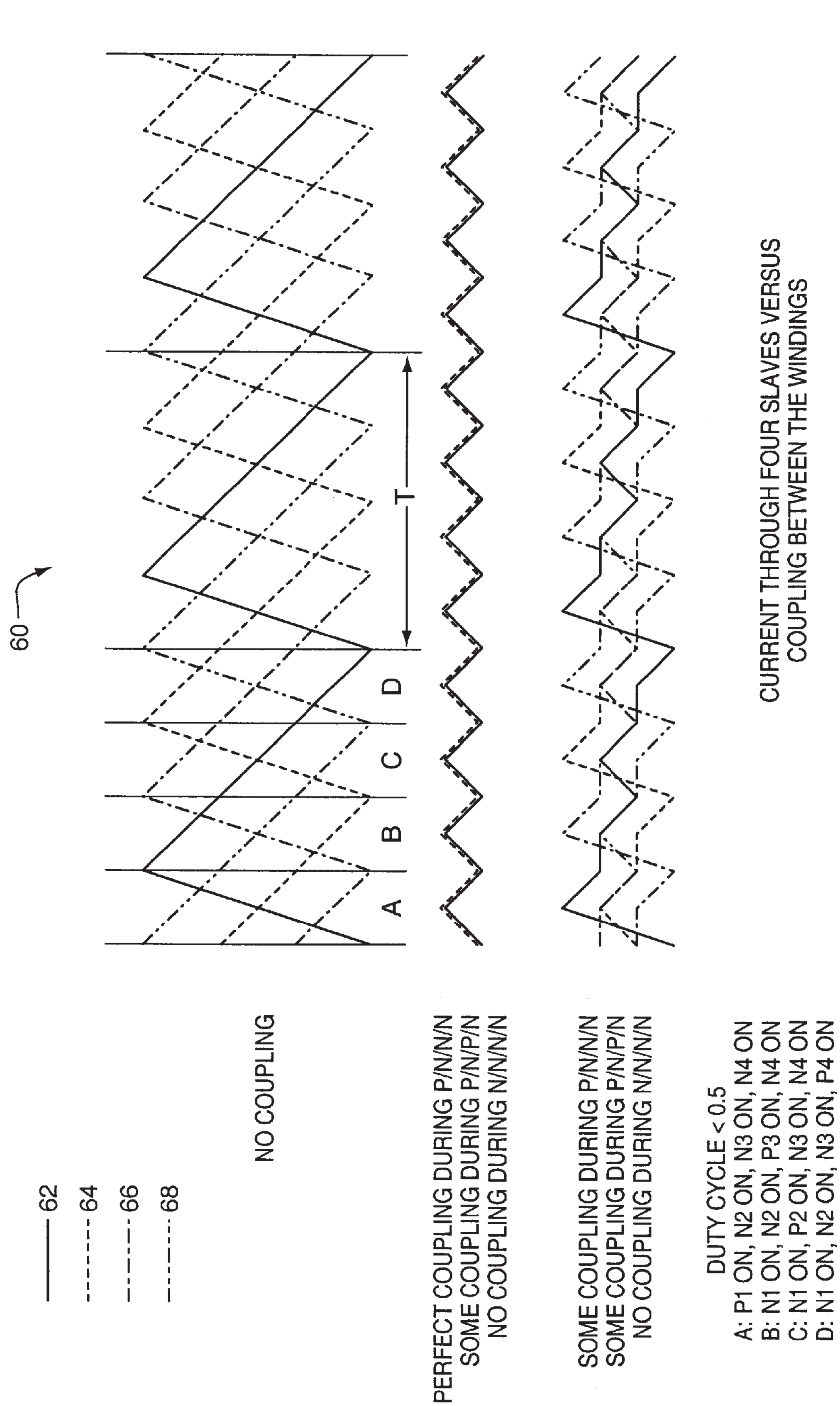

60
62
64
66
68
NO COUPLING
A
B
C
D
T
PERFECT COUPLING DURING P/N/N/N
SOME COUPLING DURING P/N/P/N
NO COUPLING DURING N/N/N/N
SOME COUPLING DURING P/N/N/N
SOME COUPLING DURING P/N/P/N
NO COUPLING DURING N/N/N/N
DUTY CYCLE < 0.5
A: P1 ON, N2 ON, N3 ON, N4 ON
B: N1 ON, N2 ON, P3 ON, N4 ON
C: N1 ON, P2 ON, N3 ON, N4 ON
D: N1 ON, N2 ON, N3 ON, P4 ON
CURRENT THROUGH FOUR SLAVES VERSUS
COUPLING BETWEEN THE WINDINGS

FIG. 5

FIG. 6

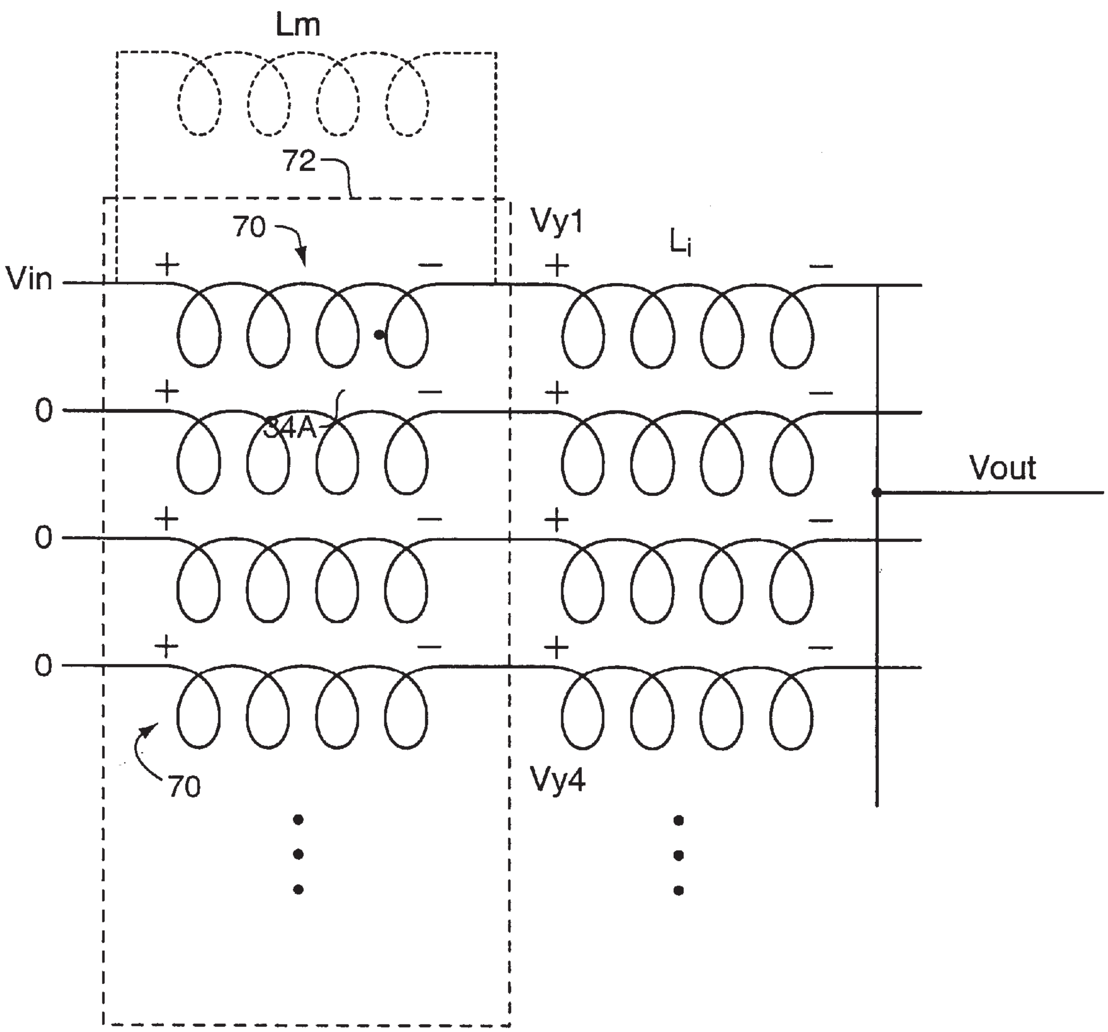


FIG. 7

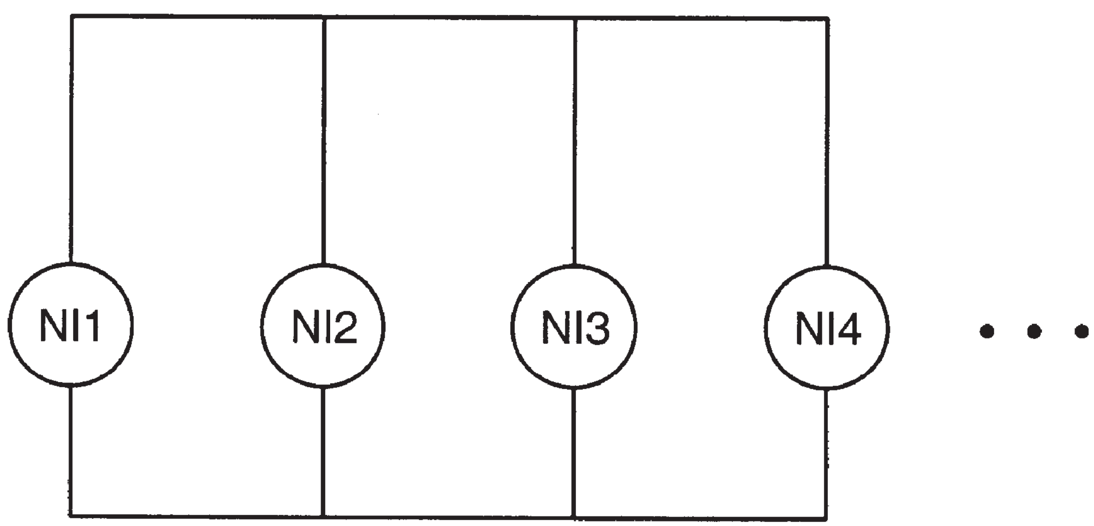


FIG. 8

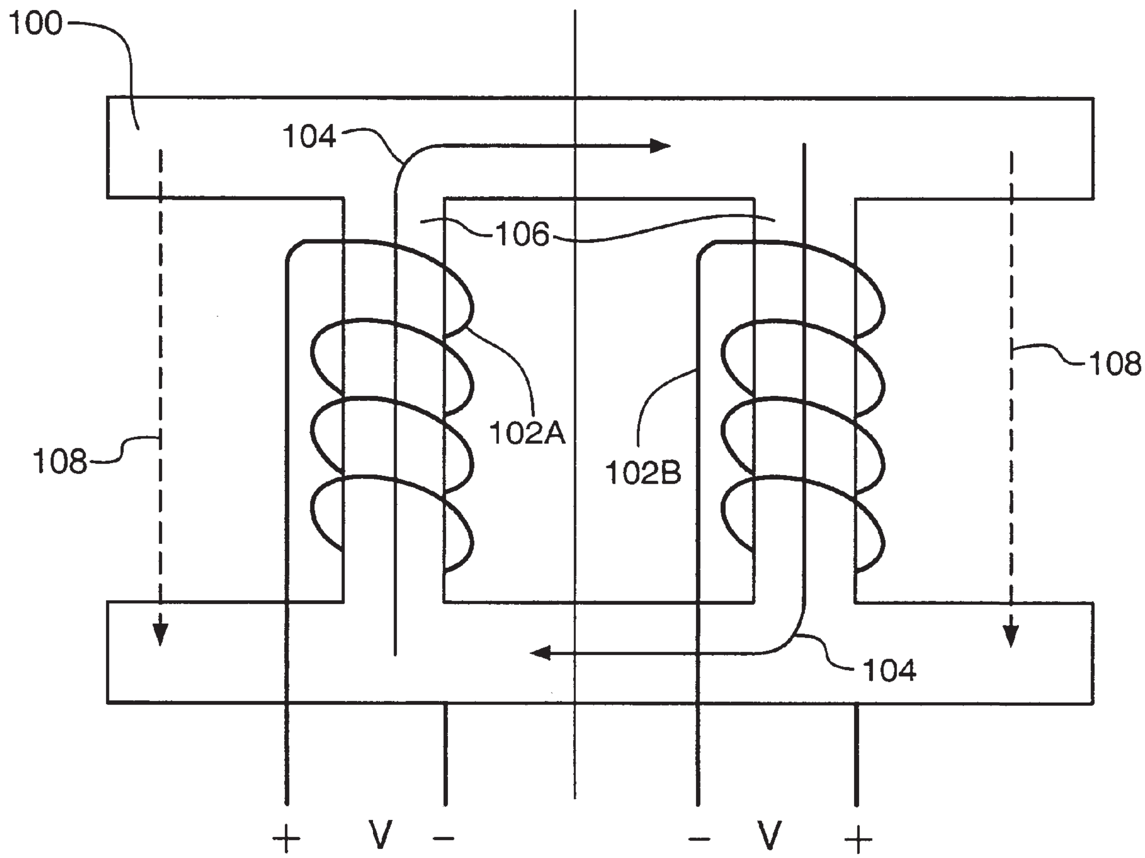


FIG. 9

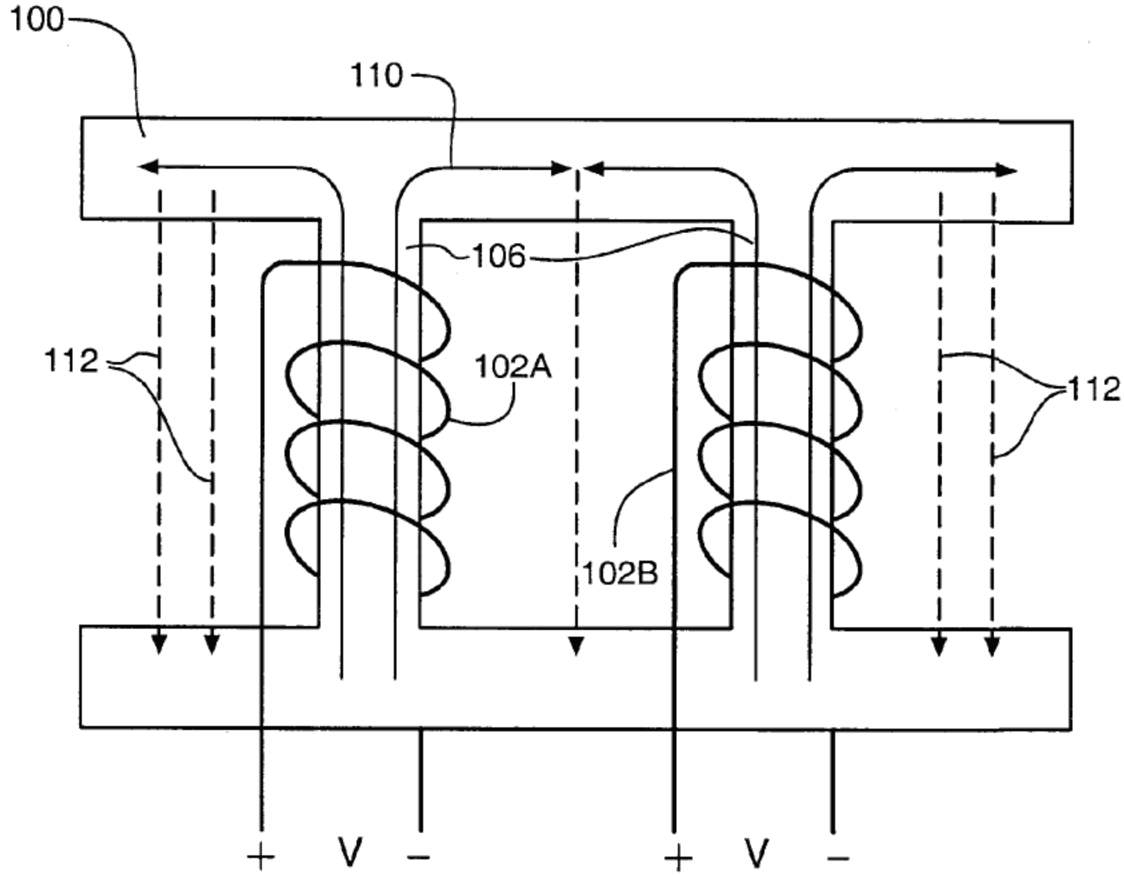
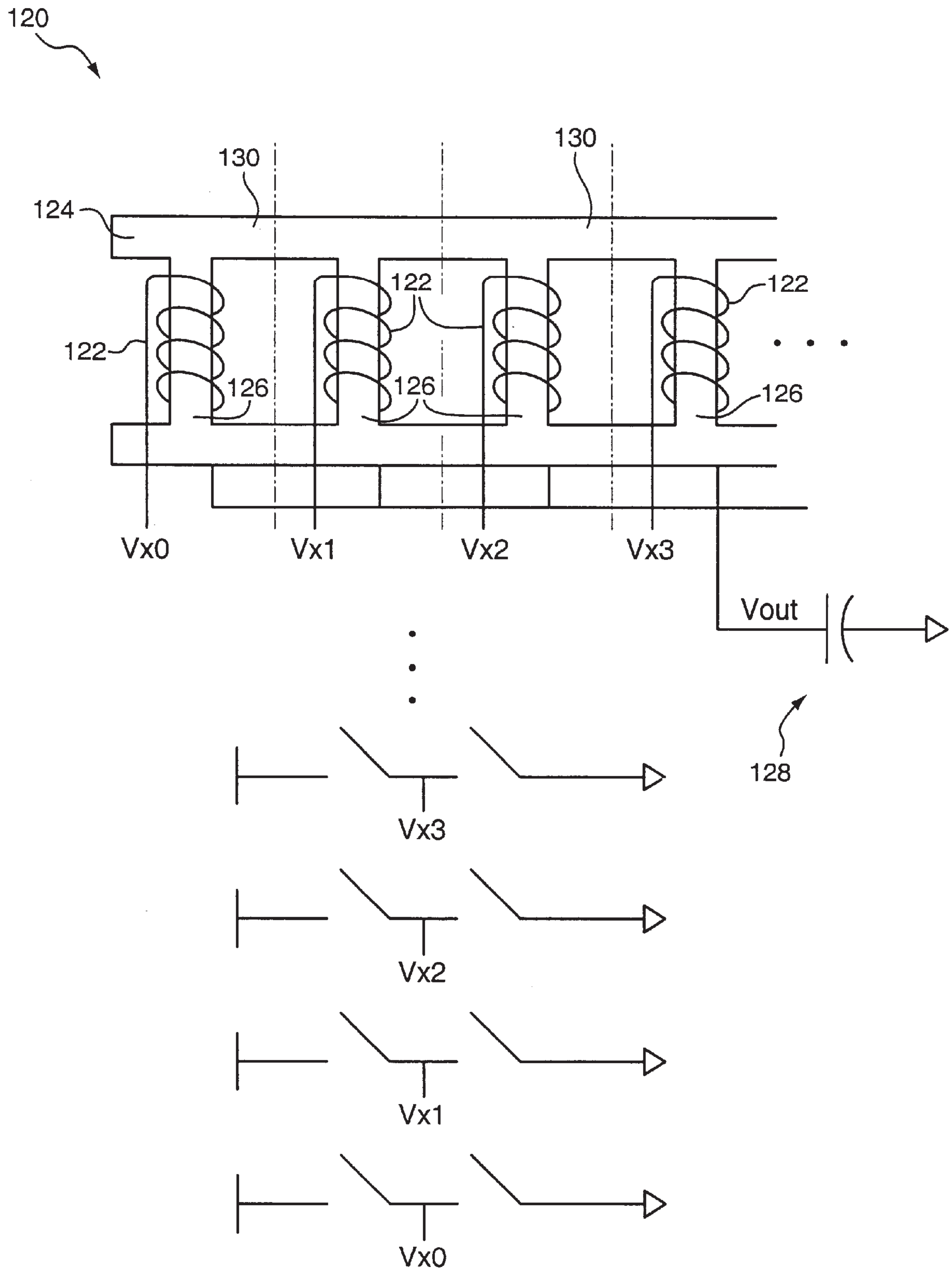


FIG. 10



120
130
130
124
122
122
122
122
126
126
126
. . .
Vx0
Vx1
Vx2
Vx3
Vout
128
Vx3
Vx2
Vx1
Vx0

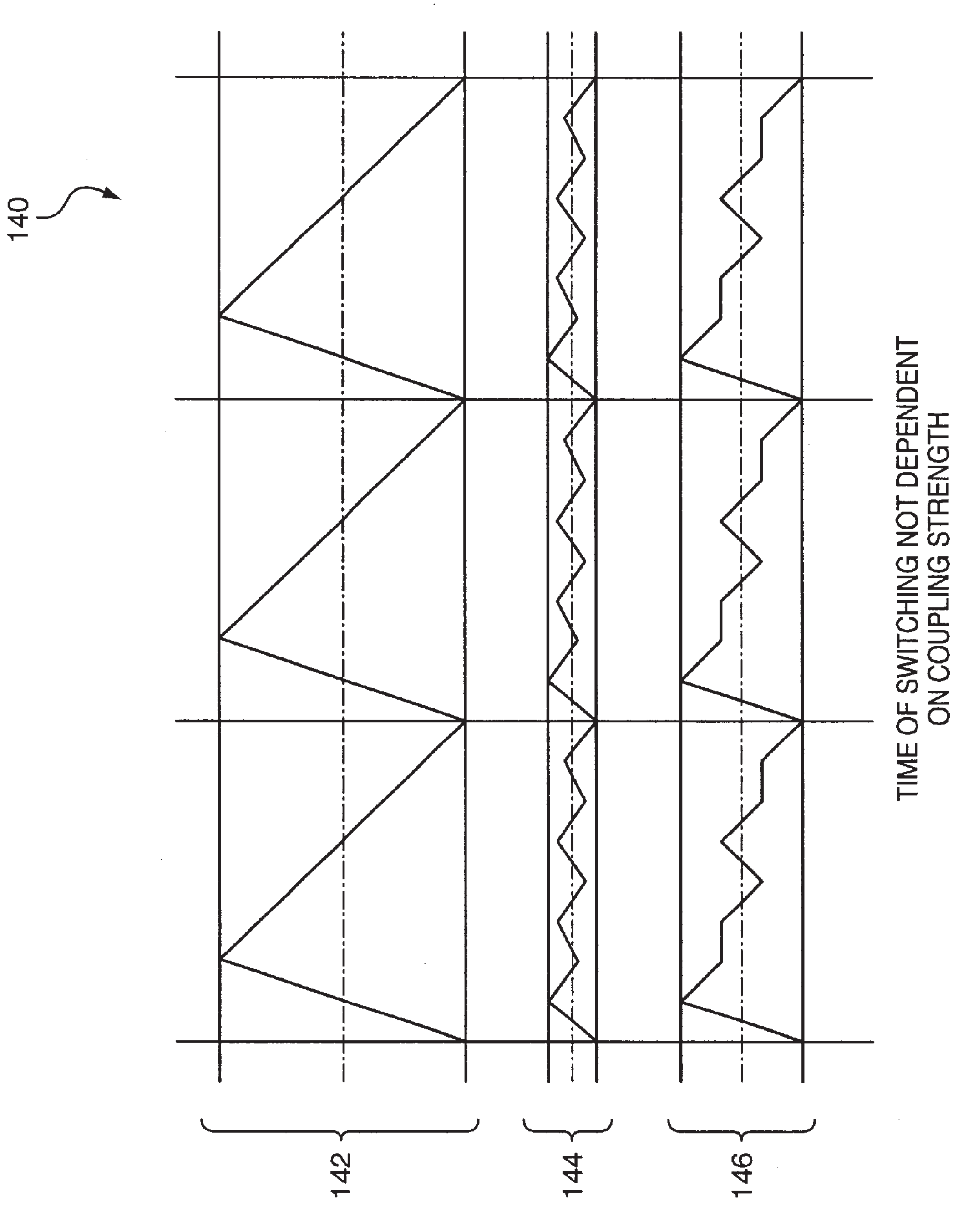

140
142
144
146
TIME OF SWITCHING NOT DEPENDENT
ON COUPLING STRENGTH

FIG. 11

FIG. 12

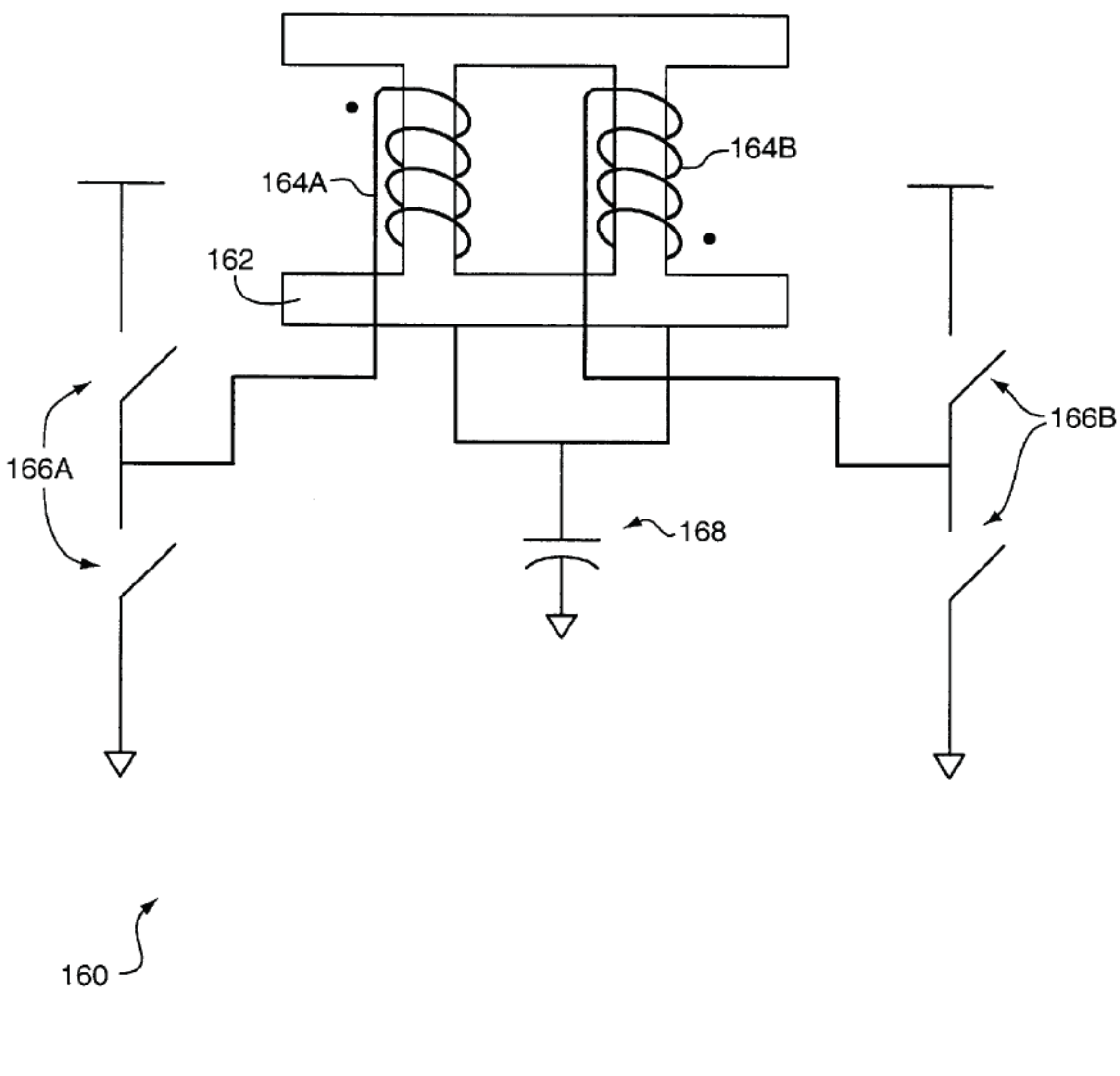


FIG. 13

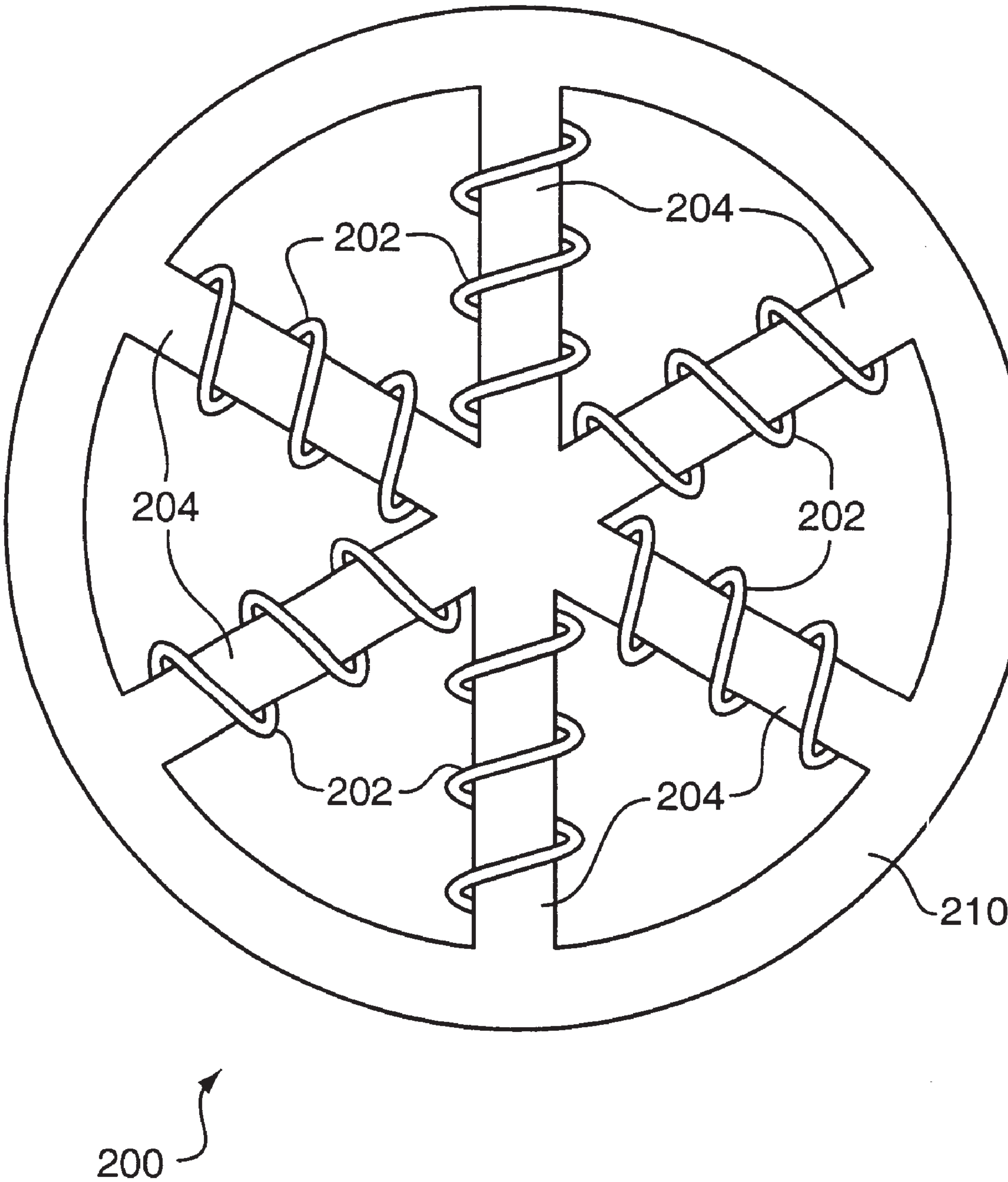
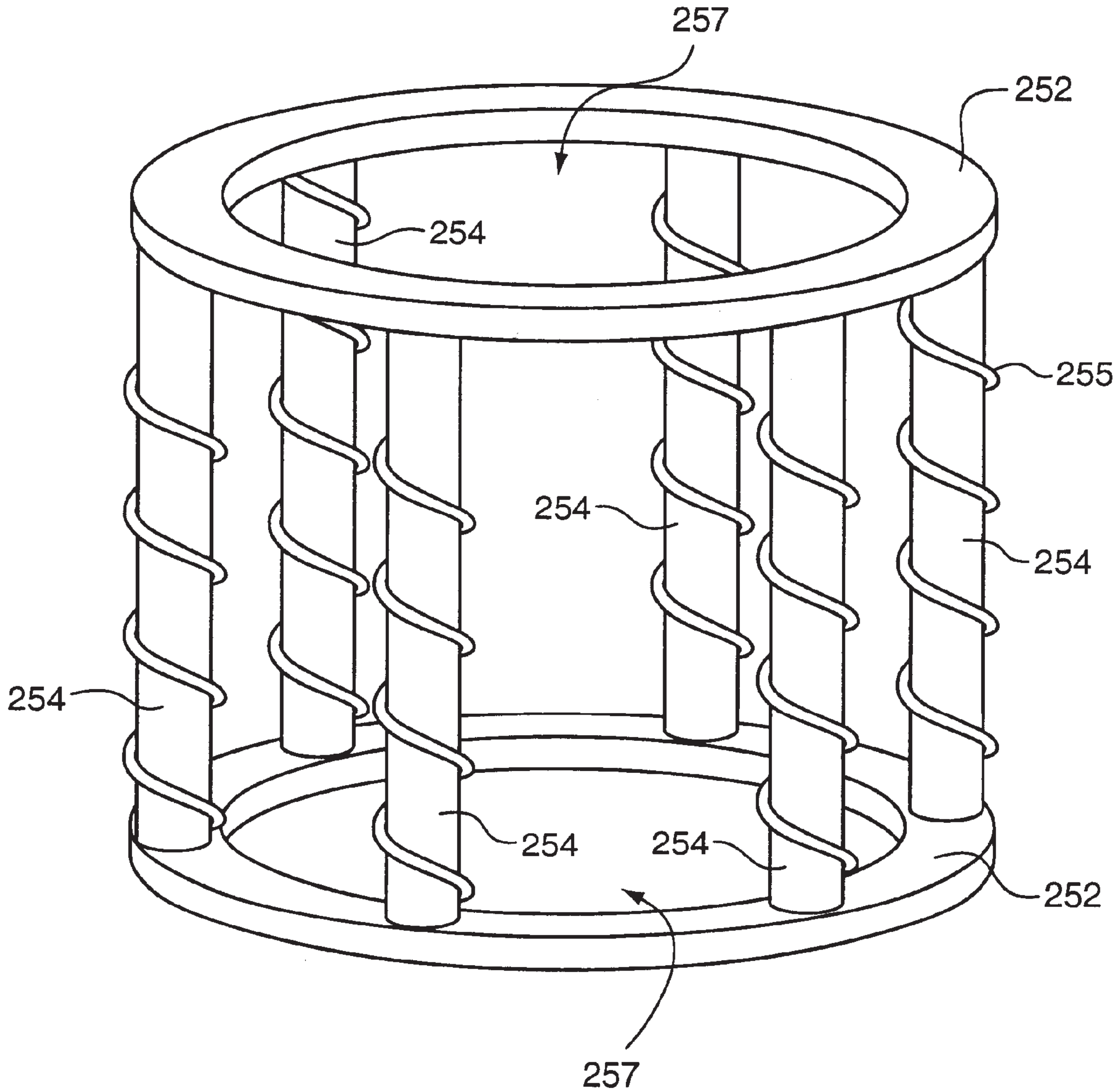


FIG. 14



VOLTAGE CONVERTER WITH COUPLED INDUCTIVE WINDINGS, AND ASSOCIATED METHODS

FIELD OF THE INVENTION

The invention relates generally to switching power converters such as the DC-to-DC buck converters and the boost or buck-boost converters.

BACKGROUND OF THE INVENTION

The parallel power units of prior art DC-to-DC converters typically couple their inputs to a common DC voltage source and their outputs to a load, such as a microprocessor. As known in the art, multiple power units replacing a single power unit can sometimes reduce cost by lowering the power and size rating of components. A further benefit is that multiple power units provide smaller per-power-unit peak current levels, combined with smaller passive components.

The prior art also includes switching techniques in parallel-power-unit DC-to-DC converters. By way of example, power units may be switched with pulse width modulation (PWM) or with pulse frequency modulation (PFM). Typically, in a parallel-unit buck converter, the energizing and de-energizing of the inductance in each power unit occurs synchronously with switches coupled to the input, inductor and ground. Additional performance benefit occurs when the switches of one power unit, coupling the inductors to the DC input voltage or to ground, are out of phase with respect to the switches in another power unit. This "multi-phase," parallel power unit technique results in ripple current cancellation at a capacitor, to which all the inductors are coupled at their output terminals.

It is clear that smaller inductances are needed in DC-to-DC converters to support the response time required in load transients and without prohibitively costly output capacitance. More particularly, the capacitance requirements for systems with fast loads, and large inductors, may make it impossible to provide adequate capacitance configurations, in part due to the parasitic inductance generated by a large physical layout. But smaller inductors create other issues, such as the higher frequencies used in bounding the AC peak-to-peak current ripple within each power unit. Higher frequencies and smaller inductances enable shrinking of part size and weight. However, higher switching frequencies result in more heat dissipation and possibly lower efficiency. In short, small inductance is good for transient response, but large inductance is good for AC current ripple reduction and efficiency.

The prior art has sought to reduce the current ripple in multiphase switching topologies by coupling inductors. For example, one system set forth in U.S. Pat. No. 5,204,809, incorporated herein by reference, couples two inductors in a dual-phase system driven by an H bridge to help reduce ripple current. In one article, Wong, *Investigating Coupling Inductors in the Interleaving QSW VRM*, IEEE APEC (February 2000), slight benefit is shown in ripple reduction by coupling two windings using presently available magnetic core shapes. However, the benefit from this method is limited in that it only offers slight reduction in ripple at some duty cycles for limited amounts of coupling.

It is, accordingly, an object of the invention to provide a voltage converter, such as a DC-to-DC voltage converter, that reduces or eliminates the afore-mentioned difficulties. One specific object of the invention is to provide a converter with two or more windings wound around a common core to preferentially maximize coupling between windings. These and other objects will be apparent in the description that follows.

SUMMARY OF THE INVENTION

In one aspect, a DC-to-DC converter is provided to generate an output voltage from an input voltage. The converter includes first and second inductive windings and a magnetic core. One end of the first winding is switched at about 180 degrees out of phase with one end of the second winding, between ground and the input voltage, to regulate magnitude of the output voltage. Each of the first and second windings is wound about a common core. A pair of windings in proximity to one another or wound about a common core forms a transformer. Of the many common electrical circuit models used to describe a transformer, familiar to those skilled in the art, the "T-model," will be used herein. The T-model comprises two leakage inductances, one associated with each winding, a common magnetizing inductance, and an ideal transformer. The inductance measured with only one of the windings on the core would be the sum of the one winding's leakage inductance and the magnetizing inductance. The first winding is wound about the core in a first orientation, but the second winding is also wound about the core in the first orientation so as to increase coupling between windings and to reduce ripple current associated with the output voltage. To clarify what is intended by the orientation of the windings, when the two windings both have positive current, the flux generated around the main magnetizing flux path by one should be counterclockwise, whereas the flux generated by the other should be clockwise. When the two windings are wound around opposite sides of a square post, both produce flux in the same direction in Cartesian coordinates, given positive current. The issue of what is meant by the same orientation is discussed further below.

In one preferred aspect, the invention is deployed in the form of a buck converter. Those skilled in the art should appreciate that modifications can be made to form a boost, buck-boost, or other converter, as described herein.

The invention has several advantages in addition to those apparent above. For example, the converter of the invention not only provides ripple cancellation in the output capacitor, but can also provide ripple cancellation in the windings and in the switches. It can do so with two or more windings. Moreover, ripple reduction is minimized with "perfect" coupling between the windings—a feature distinctly absent in the prior art. In a further advantage, the invention operates with a magnetic core shaped in one of multiple geometries, whereas the prior art describes only certain shapes. By way of example, Wong, Investigating Coupling Inductors in the Interleaving QSW VRM, IEEE APEC (February 2000), requires E cores with center legs, and U.S. Pat. No. 5,204,809 discloses a doughnut shaped core. In accord with the invention, the core may take several forms, described below, and additionally can provide more power than an E core of the same physical size, because space for a center leg is not needed. Part of the distinction between the prior art and the present invention can be better understood with reference to the intended use of the inductors. One purpose of integrating two separate inductors in the prior art was to save space on a printed circuit board. Coupling between windings on a common core was, in fact, not desired, except to decrease the number of components and overall component area. The present invention actively seeks to couple windings together on the same core.

The invention also provides methods for magnetically coupling inductive devices in a parallel, multiphase power unit regulator topology to reduce current ripples. The method includes the steps of: orienting, in like direction, first

and second windings about a common core to increase coupling between the windings; and alternatively activating one end of the first winding about 180 degrees out of phase with one end of the second winding, between a control voltage and the input voltage, to regulate magnitude of the output voltage, wherein magnetizing inductance substantially equals an inductance of the first winding with the core absent the second winding. In one preferred aspect, the control voltage is ground.

The methods of the invention thus enable the use of smaller inductances for transient response optimization without incurring additional current ripple. The invention accordingly lends itself to scalability in coupled magnetic and multiphase topologies. As the number of phases increases almost arbitrarily, the resulting current ripple will continue to be reduced. Further benefits are achieved in replacing standard separate inductors, one per power unit, with a single combined magnetic structure of the invention, including: size reduction, pick and place assembly time and error reduction, lower design cost, implementation, and ease of manufacturing DC-to-DC converters.

Those skilled in the art should also appreciate that the use of coupled magnetics in accord with the invention can reduce current ripple when switching at a particular frequency. If the original switching frequency is lowered, then magnetic coupling will in fact boost each individual winding's current ripple frequency back to the original frequency. Accordingly, the switching frequency of the switches will be reduced with the current ripple being the same as with no coupling. This lower frequency switching results in higher system efficiency. In the various implementations of the invention, when same side switches in different power units operate simultaneously, as they might during transients, then the slopes of inductor currents in each power unit will be substantially maximized. Therefore, both steady-state ripple reduction (by minimizing inductor current slew rates) and short-term transient response enhancement (by maximizing inductor current slew rates) can be achieved simultaneously.

The invention also provides a multi-phase DC-to-DC converter for providing an output voltage from an input voltage. The converter has N ($N \geqq 2$) inductive windings alternatively switched between a control voltage and the input voltage to regulate magnitude of the output voltage. Each of the N windings has a turn-on switching transition separated in switching phase by about 360/N degrees from any other of the windings. Each of the windings also has a turn-off switching transition separated in phase by about 360/N degrees from any other of the windings. Each of the windings is wound on a common magnetic core wherein magnetizing inductance is greater than about three times the leakage inductance of any one of the windings. Each of the N windings is wound about the core in like orientation to increase coupling between windings and to reduce ripple current associated with the output voltage.

In other aspects, the invention provides core structures suitable for multiple windings in a converter such that the multiple windings collectively excite at one excitation pattern, and collectively do not excite at another excitation pattern. By way of example, an oval-shaped core structure and a square core structure are suitable for two windings; however neither are suitable for more than two windings. As another example, a core structure in the shape of a "ladder"—where one winding is wound around each rung of the ladder—can support two or more windings. Accordingly, by way of specific example, a N-rung ladder structure can support N windings, if desired ($N \geqq 2$). Another core structure supporting more than two windings, in accord with the invention, includes a wheel-shaped structure with each of the windings wound around separate spokes. Again, N windings may be deployed providing N spokes support the windings. Yet another core structure supporting the invention includes a structure in the shape of two plates (e.g., disks, rectangles, or other shape) coupled by N columns. In each of the aforementioned structures, excitations of the windings can be made to excite all windings, or not. In the case of multiple excitation, for example, by exciting each winding in a ladder configuration, one can make each winding impart flux into neighboring windings in a positive fashion, with flux flow constructively interfering. Alternatively, flux flow from one winding can be made to effectively collide with flux flow of another winding thereby decreasing interaction between windings.

These and other aspects and advantages of the invention are evident in the description which follows and in the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows one DC-to-DC converter system constructed according to the invention;

FIG. **2** shows a model operatively illustrating a circuit for a two-wide coupled magnetic device used in a DC-to-DC switching power supply, in accord with the invention;

FIG. **3** shows a model operatively illustrating an electrical circuit analog for two magnetically coupled windings, in accord with the invention;

FIGS. **3**A and **3**B illustrate winding orientations to a core, in accord with the invention;

FIG. **4** illustrates various waveforms showing benefits of using two power stages with coupled magnetics in accord with the teachings of the invention;

FIG. **5** illustrates various waveforms showing benefit of obtaining ripple reduction with N=4 power stages, each with a switching device coupled into a single coupled magnetic core structure, in accord with the teachings of the invention;

FIG. **6** shows a circuit model for a N wide coupled magnetic device used in a DC-to-DC switching power supply according to the teachings of the invention;

FIG. **7** shows an electrical circuit analog, similar to FIG. **3**, that models N magnetically coupled windings, with zero reluctance appearing as zero resistance in the circuit branches;

FIG. **8** shows a magnetic device with a continuous square core shape, and windings with equal and opposite voltage excitation, in accord with the invention;

FIG. **9** shows the device of FIG. **8** but with an equal and same sign voltage excitation to the two windings;

FIG. **10** shows a multiphase, paralleled power unit DC-to-DC switching power supply with a composite magnetic structure, constructed according to the invention;

FIG. **11** graphically depicts results in controlling high- and low-side switches based on a current envelope, and as a function of coupling, in comparing coupling effects in a converter;

FIG. **12** shows a dual phase, paralleled power unit DC-to-DC switching power supply with a composite magnetic structure, constructed according to the invention;

FIG. **13** shows a wheel and spoke core structure constructed according to the invention; and

FIG. **14** shows a two-ring and column core structure constructed according to the invention.

DETAILED DESCRIPTION OF THE INVENTION

FIG. **1** shows a DC-to-DC converter **10** constructed according to the invention. Converter **10** converts an input

voltage (here shown as first and second input voltages Va, Vb) to an output voltage (Vc). Converter **10** has two switching devices **12**, known in the art, coupled to the input voltage Va, Vb and responsive to control signals to electrically connect windings **14** to Va, or, alternatively, to Vb. There are two windings **14**A, **14**B shown in FIG. **1** and wound around a magnetic core **16**. Windings **14**A and **14**B are wound in like orientations about core **16**. As will be described in more detail below, core **16** (here in the shape of a "square") can take many shapes, and core **16** can be considered as two "rungs" **16**A, **16**B, and two "risers" **16**C, **16**D forming the square core shape. Windings **14**A, **14**B are thus wound about rungs **16**A, **16**B, respectively.

During activation (i.e., when windings are coupled to a voltage, Va or Vb), windings **14** effect a change of flux **18** in core **16**. In most types of converters, one of Va and Vb will the more positive than Vc, and the other will be less positive. Without loss of generality, it is assumed that Va is more positive than Vc and Vb is less positive (Va>Vc and Vb<Vc). More particularly, when winding **14**A is activated by Va, an increase of flux in direction **18**A is generated; when winding **14**A is activated by Vb, an increase of flux in direction **18**B is generated; when winding **14**B is activated by Va, an increase of flux in direction **18**C is generated; when winding **14**B is activated by Vb, an increase of flux in direction **18**D is generated. Accordingly, by the techniques of the invention, windings **14** are preferentially activated so as to interact together, and then alternatively so that there is little interaction. Specifically, by activating winding **14**A with Va to generate flux **18**A, and by activating winding **14**B with Vb to generate flux **18**D, one can achieve interaction since flux **18**A flows into winding **14**B and rung **16**B, and flux **18**D flows into winding **14**A and rung **16**A. A similar interaction is achieved by activating winding **14**A with Vb while activating winding **14**B with Va; in this case flux **18**B flows into winding **14**B and rung **16**B, and flux **18**C flows into winding **14**A and rung **14**A.

Yet it is also desirable at times to minimize the interaction of windings **14**A, **14**B with one another, in accord with the invention. This is achieved by simultaneously connecting windings **14**A, **14**B to Va, or, alternatively, to Vb. With such activation by Va, flux **18**A "collides" with flux **18**C; with such activation by Vb, flux **18**B collides with flux **18**D. There is thus little flux flow and thus little interaction between windings **14**A, **14**B with like activation by Va or Vb.

In one preferred embodiment, Vb is ground, and Vc is the output, facilitated by output electronics **17**, so that converter **10** operates like a buck converter. In another embodiment, Vc is input, Vb is ground, and Va is the output, so that converter **10** operates like a boost converter. In yet another embodiment, Va is the input, Vb is the output, and Vc is ground, so that converter **10** operates like a boost converter. Further such permutations are possible, in some cases using more switches **12**. In Robert W. Erickson's *Fundamentals of Power Electronics*, p. 149–151, incorporated herein by reference, there are shown twelve different non-isolated dc-dc converters, any of which is the basis for another embodiment of this invention, in which multiple parallel out-of-phase sections are used with the inductors coupled as described herein. Furthermore, transformer-isolated converters such as forward converters that use inductors separate from their transformers are the basis for other embodiments of the invention, as described above. Transformer-isolated topologies that use the transformer as the main inductive element, such as the flyback converter, are the basis for other embodiments of the invention, as described above, except that the coupled inductive structure has pairs of windings replacing each single winding.

With selected operation and activation of windings **14**A, **14**B, there is very little ripple associated with the output current. The prior art has not taught maximizing coupling between windings on a common core to reduce ripple current. This coupling is achieved in part because of the like orientation of windings **14**A, **14**B about rungs **16**A, **16**B, and in part by using as little as practical air gap in the flux path **18** through the two windings. Each winding **14**A, **14**B has a leakage inductance and a magnetizing inductance, as defined by terminal characteristics of the standard T-model. In the preferred embodiment of the invention, the magnetizing inductance is greater than at least three times the leakage inductance of either winding.

The invention of preferred embodiments thus involves the use of magnetic core structures that enhance coupling among windings coupled with the structures. For illustrative purposes, the benefits of such coupling can be shown as a model employing an ideal transformer, as in FIG. **2**. Specifically, FIG. **2** shows a circuit model **30** modeling a coupled, two winding magnetic device constructed with the teachings of the invention to generate an output voltage Vout. The dotted line **32** represents the ideal transformer, within which reside two windings **34**A, **34**B. Winding **34**A is shown connected between control voltages Vx**2**, Vy**2**; winding **34**B is shown connected between control voltages Vx**1**, Vy**1**. Two leakage inductances L_1, L_2—one for each winding **34**A, **34**B, respectively—connect to the ideal transformer **32**. Magnetizing inductance Lm connects in parallel to ideal transformer **32**. For transformer applications, those skilled in the art will appreciate that one winding **34** may be used for source excitation delivering power, and that the other winding **34** may be used for a load receiving power; however in accord with the teachings of the invention, the operations of windings **34** include the excitation of both windings **34**A, **34**B.

More particularly, to explain how multiple windings on a single core (e.g., as in FIG. **1**) interact, the "perfect" coupling case is described first. With perfect coupling between windings **34**A, **34**B, the value of Lm, the magnetizing inductance, is infinite. Infinite magnetizing inductance means zero reluctance within the core, which in turn implies that no net winding current can ever flow, even with changing flux through the core, where net winding current is used to denote the different between the two winding currents. In FIG. **2**, current i_1 represents winding current for winding **34**B, and current i_2 represents winding current for winding **34**A. Changes in winding current i_1, i_2 will only occur when there is a change in the flux traveling outside the perfect flux-conducting core. Flux in a zero reluctance core will travel without "resistance" from any point within the core to any other location. Where the flux flows, and in what magnitude, are determined by the applied electrical excitations and reigning constitutive laws.

One condition in ideal transformer model **32** is that the sum of voltages across windings **34**A, **34**B is zero. An additional constraint may be considered with respect to FIG. **3**, showing an electrical circuit **40** electrically modeling the magnetic schematic of FIG. **2**. More particularly, when the magnetic structures of the invention afford good coupling between windings, the associated magnetic path reluctances are very low. In FIG. **3**, "good coupling" is represented by Rm approaching zero; Rm being the reluctance through the core. With Rm approaching zero, the magneto-motive force (MMF) excitations (analogous to voltages) with values NI**1** and NI**2** are in parallel. Accordingly, NI**1**=NI**2**, and currents

i_1 and i_2 (FIG. **2**) are equal. The magnetizing reluctances Rm (analogous to resistances), will approach zero for perfectly coupled windings as Lm approaches infinity. In this case, only the leakage reluctances R_1 remain.

The sum of voltages across windings **34**A, **34**B within an ideal transformer **32** equals zero. Because currents i_1, i_2 are the same, the voltages across the two leakage inductances L_1, L_2 are also the same. Accordingly, when Vx**1** switches to Vin and Vx**2** to ground, as in a high-side and low-side synchronous buck converter configuration, then Vy**1**=Vy**2**=Vin/2 and the voltages across windings **34**A, **34**B add as (Vin−Vin/2)+(0−Vin/2)=0. Alternatively, when Vx**1** and Vx**2** are both switched to ground, then Vy**1**=Vy**2**=0, then the voltages across the windings **34**A, **34**B add as 0+0=0.

FIGS. **3**A and **3**B provide further understanding of how windings are properly oriented in accord with the invention. FIG. **3**A illustrates a winding and core structure **41** with the windings **42**A, **42**B placed on the lower core legs **43** rather than on the two sides **44**. In structure **41**, windings **42**A, **42**B are considered in the same orientation because a current flow toward Vc in both leads to flux flow in opposite directions around the main, ungapped path of the core **45**, just as in FIG. **1**. Accordingly, the flux produced by equal currents in both windings **42**A, **42**B leads to flux in the leakage path (shown here a gapped center-leg **47**).

FIG. **3**B is similar to FIG. **3**A, again with windings **42**A', **42**B' properly oriented. However, the physical orientation of windings **42**A', **42**B' has been reversed from FIG. **3**A, but with electrical connections to Vx**1**, Vx**2** also reversed. The net effect is that flux directions for a particular current direction is the same as for both FIG. **3**A and FIG. **3**B.

The above description illustrates certain advantages of the invention. In regulators or converters with uncoupled inductors, each switch would be operated with some nominal period T, as shown in FIG. **4**. The slopes of currents through the inductors are (Vin−Vout)/L_l during high-side switch conduction, and −Vout/L_l during low-side switch conduction. Once coupling is introduced, then the voltage across both inductors becomes (Vin/2−Vout)/L_l, when one power unit's high-side switch is on with the other unit's low-side switch on. The result of the coupling, then, is smaller ripple at twice the frequency, as shown in FIG. **4**. FIG. **4** graphically illustrates a chart **50** of current ripple between two power units versus coupling between the windings. Line **52** represents data for the first power unit and line **54** represents data for the second power unit for each coupling scenario set forth on the left side of chart **50**. A–E represent different activation cycling, as indicated, for a duty cycle <0.5. As annotated, P represents when a winding is switched to Vin; and N represents when a winding is switched to ground. During N/N, there is no interaction between windings. Based on the formula (Vin/2−Vout)/L_l, it becomes clear that for certain Vin, Vout combinations, zero ripple is achieved. In cases where Vout=Vin/2, then one high-side switch and one low-side switch is closed within the two power units; the value of leakage inductance L_l does not matter. The leakage inductance can therefore be lowered to improve the transient response, during which there might be simultaneous turn-on of both high-side devices, or both low-side devices.

Note that the per-power-unit ripple current decreases, and the effective ripple frequency increases, with magnetic coupling even when the duty cycle is not 50%. It is therefore possible to lower the inductance L_l and still achieve ripple currents that are smaller than the uncoupled ripple currents. As a result, use of the magnetically coupled constructs of the invention can improve the speed of transient response to load current changes while simultaneously reducing ripple currents.

It is also useful to understand what happens in the normal case when Lm is not infinite, and when the core does not have perfectly zero reluctance. In this case, any time there is a non-zero voltage across the ideal transformer windings **34**A, **34**B (FIG. **2**), then the magnetizing inductance current will ramp up or down. As a result, the leakage inductances L_l may not share the exact same voltage since the current derivatives through them are also not the same. However, even if Lm is as small as 3L_l, the overall ripple cancellation in each power unit will still be significant.

By way of further explanation, the following describes metrics associated with good coupling between windings. The higher Lm is compared to L_l, the better the coupling. Specifically, when σ=Lm/L_l is infinite, there is perfect coupling. Other references use a different formula to define the coupling effect: k=Lm/(L_l+Lm), which is equal to one when there is perfect coupling. k=1 is the same condition as infinite σ. The following formula numerically illustrates how much current ripple can be reduced: resulting ripple/original ripple=(σ+1−D(2σ+1))/((1+2σ)(1−D)), where D=Vout/Vin (the duty cycle). As σ goes to infinity (or k goes to 1) for "perfect" coupling, the resulting current ripple is minimized. For D=0.5, the resulting ripple equals zero.

In the prior art, with k=1, the ripple reduction no longer functioned properly. In designing systems with prior art methods, therefore, one would have to take care in designing to some optimal amount of coupling as quantified by k or σ. But even with such a coupling, the overall ripple reduction would not be more than about 20 or 25%. Using the methodology of the invention, ripple reduction is seen with improved coupling, even with perfect coupling.

Note that the above two-power-unit discussion applies also to N power units. With two power units, it is assumed that one unit is switched 180 degrees out of phase with respect to the other. In the N-power unit case, the switching of the units is spread (or "phased") evenly through each overall switching period, as shown in the top of FIG. **5**. Specifically, FIG. **5** shows a graph **60** similar to FIG. **4** but with comparison of four power units, shown as lines **62**, **64**,**66**,**68**.

FIGS. **6** and **7** are the corollary of FIGS. **2** and **3** except with an arbitrary number N of power units **70**. With perfect coupling, the same constraints apply: the sum of all voltages within the ideal transformer **72** equals zero; and the currents in all leakage inductances L_l are the same, since Rm=0. As a result of these constraints, the voltage at all Vy will be Vin/N when one high-side switch among all power units **70** is on. The slope of current in each inductor **70** is (Vin/N−Vout)/L_l, which is a reduction from (Vin−Vout)/L_l. The value Vy=Vin/N is valid only when one of the power units' high-side switches is on. When enough power units are phased across one period, or when the duty cycle is high enough such that two or more phases may simultaneously have an activated high-side switch, then Vy=2Vin/N, or 3Vin/N, etc. Hence for that moment, the rising current slope (mVin/N−Vout)/L_l, with m>1, is higher than (Vin/N−Vout)/L_l. In subsequent periods when only one high-side switch is on, then Vy=Vin/N and the overall ripple is still reduced. In FIG. **7**, Lm is deemed infinite, and each MMF (NI**1**–NI**4**) is equal when the reluctances are zero. The resulting fluxes may not be zero, however, even if currents are equal.

When coupling is imperfect (i.e., Lm is not infinite), then like the earlier case the current slopes among each power

unit's winding currents may not always be the same. FIG. **5** shows how the current waveforms look for no coupling (top), perfect coupling (middle), and moderate ($0 \leqq Lm \leqq$ infinity) coupling. Even for moderate coupling, there is reduction in the AC peak-to-peak current ripple. Similarly, if L_l is not matched across all windings, then ripple cancellation may not be uniform for each power unit. However, the overall ripple reduction, compared to uncoupled magnetics, will be substantial within each power unit.

As with two phases, when the coupling is perfect, the ripple reduction is maximized. Similarly, no matter how many phases, better coupling (even perfect coupling) means better ripple reduction. In designing systems of the invention, coupling is preferably maximized. L_l, the leakage inductance, may also be adjusted in order to optimize for transient responses. Fortunately, Lm only needs to be about three times larger than L_l, but the value exactly for Lm is not critical.

As noted above, the magnetic core structures described herein are also desirable features of the invention. FIG. **8** for example shows a magnetic core **100** and windings **102A**, **102B** arranged such that the core has a square shape, including core legs or rungs **106**. In one example, windings **102A** and **102B** are exited with equal voltage magnitudes, but with opposite signs, so that the direction of increase in flux **104** developed in each winding's rung **106** is opposite from the other; and the resulting flux generally flows around the square as shown. Some small leakage flux also flows as shown in dotted lines **108**, but since the permeability of the core is much higher than that of the medium outside the core (typically air), flux **104** chooses core **100** as the permeability path. As a result of the flux following a higher permeability path, the net inductance seen at each winding **102** with this excitation is higher, and thus the net current ripple is lower. In other words, low reluctance path **104** enables flux change with very little winding current change compared to higher reluctance paths (such as leakage path **108**).

FIG. **9** shows the same core **100** and windings **102A**, **102B** of FIG. **8**; except that the windings **102A**, **102B** of FIG. **9** are excited with voltage of the same sign and magnitude. Due to symmetry, flux cannot effectively flow through core **100** along permeability path **112**, and all flux developed with this excitation essentially flows, as shown, in leakage paths **110**. Ripple current caused by excitation of FIG. **9** is higher than in FIG. **8** since higher reluctance paths of flux relate to larger winding current deviations. The two paths—leakage path **112** and the high permeability inner-core path **110**, correspond to the L_l and Lm inductances in the above-described models.

As described briefly above, FIG. **4** illustrates reduction ripple with coupling between windings. In the top portion of graph **50**, the uncoupled peak to ripple is shown at the switching frequency in each phased power unit. In the middle portion of graph **50**, the ripple is reduced because of perfect coupling. The bottom portion of graph **50** shows currents with reduced ripple in the presence of imperfect coupling (or finite Lm). When both low-side devices are on, then the excitation on the two windings is in the same direction, as in FIG. **9**, and flux will follow only the leakage paths **112**. As a result, each winding's falling current slope is the same as if there were no coupling between the two inductors. However, when one high-side switch and one low-side switch is on, then the flux is shared, as in FIG. **8**, with the result of lower reluctances in the flux path and smaller current ripple than had there been no coupling. Good coupling during this excitation means that the change in flux in each winding is nearly equal and opposite in sign. As a result, the direction of current change in each winding will be the same; and the current in a winding whose low-side switch is on will go up since it is coupled to the winding whose highside switch is on. At the same time, as shown in FIG. **4**, the effective frequency of the current waveform in each winding has multiplied by two, even though the switching at each winding remains at the original frequency.

In FIG. **10**, there is shown a coupled magnetic structure **120** with more than two windings **122** on a common core **124**. Core **124** is in a "ladder" configuration with a plurality of "rungs" **126** coupled with windings **122**. In each case, windings **122** are wound with like orientation on rungs **126**. Structure **120** also has a capacitive output **128** linked to Vout. In prior art uncoupled inductors, ripple current cancellation occurs only in capacitor **128**. Structure **120** is thus intended to be used in a DC-to-DC converter with more than two parallel power units, generating Vout from the input voltage Vx. FIG. **11** shows the results of operation of structure **120** in the current ripple when excited by properly phased power units, as a function of coupling. In order for proper phasing and current ripple to occur, a properly phased set of PWM pulses needs to synchronously activate or disable the switches within each power unit (e.g., switches **12**, FIG. **1**). N phases are spaced evenly within 360 degrees (or timed evenly within one period) in order for the ripple cancellation to be evenly distributed among all power units. Properly switched, each phase will experience an increase in its effective current ripple frequency. In FIG. **11**, the top part **142** of chart **140** illustrates the case of no coupling; the middle part **144** illustrates the case of excellent coupling, such that the interaction during P/N decreases ripple, and the lack of interaction during N/N allows fast transient response; and the lower part **146** illustrates the case of limited coupling.

Thus reducing ripple current in accord with the invention is further enhanced with more magnetic branches in the common magnetic core structure. At some point, the ripple current, which can easily be as high as ten amps in certain applications, can be reduced to below one amp. As a result, the parallel power units may be thought of as current sources. The structure of FIG. **10** can thus be viewed as a multiplication of the structures shown in FIG. **8** and FIG. **9**. It is possible to add on sections (e.g., rungs **126** and windings **122**) to create a larger, scaled, one-piece device. The core may be constructed as a single piece, or may be constructed by joining pieces, one piece per phase, or one per two phases, etc. This modular scheme has the advantage that it is possible to construct converters for different power ratings using different numbers of sections, while only stocking one size of core piece and avoiding investment in tooling for different cores.

Another advantage is that systems that use coupled magnetic structures can require less area on printed circuit boards, compared to using N power units with N uncoupled inductors, which would need additional space around the inductors. The benefits of the invention are thus apparent, and with one single coupled inductor device, most of the surrounding area is eliminated, saving space.

As the structure grows larger, coupling between all windings may become less perfect. It is thus recommended that the different phases be laid out such that the physically adjacent windings are as far apart as possible in phase, so that the stronger coupling between adjacent phases has the maximum ripple reduction effect. In any event, perfect coupling is not required to achieve improved current ripple cancellation. As described below, slightly less than perfect coupling can also be used advantageously.

The above-described structures show the benefits of forming multiple windings on a common core, with windings in like orientation and proper excitation. Certain detail can be added:

1) The leakage path is usually of relatively high reluctance, compared to the magnetizing flux path. The leakage flux path may be a natural result of the core structure and winding placement, in which case no additional structure is needed. Or, the leakage path may use an explicitly gapped high permeability core leg or shunt, un-gapped low permeability core leg or shunt, or a core extension, that reduces the reluctance of the leakage air path. The leakage path may also be effected by some combination of these additional structures.

2) It is desirable that each winding independently generate magnetic flux in its own core segment (e.g., a rung), and to couple that flux into a low reluctance core. With a ladder structure as in FIG. **10**, the fluxes in each winding **122** are coupled into core **124** appropriately. When all windings **122** are excited with the same current, only the leakage paths are effectively available for flux, and flux does not effectively travel from one winding **122** to another. When certain windings **122** are excited by high-side switching, and some windings **122** by low-side switching, a changing flux is produced. The new flux travels from one winding **122** to another. With ladder type multiple winding (N>2) magnetic structures, as in FIG. **10**, windings should be with the ladder rungs, and not on the ladder risers **130** (except for the windings at either end, for which any position around the same flux path is equivalent).

The following bullets summarize certain advantages of the invention:

Reduced current ripple. This reduces losses in the inductor windings and in the switches. This can lead to fewer paralleled units with higher current ratings, and/or less expensive parallel power units with relaxed current ratings. Smaller peak currents aid in improving reliability of devices. Although the overall ripple current reduction in the output capacitance is the same as it is for an uncoupled multi-phase converter, it can be difficult to realize the full benefit of that cancellation in an uncoupled multi-phase converter, because large ripple currents must flow between the outputs of the different phases. For example, in some physical arrangements with multiple parallel output capacitors, the large ripple currents flowing between phases may lead to voltages differences between these capacitors, despite the intention to have them in parallel, all at the same voltage. The results of this include local ripple currents in individual capacitors that do not cancel as intended, and sometimes difficulties is controlling the output voltage, that is now different at different points.

Smaller inductance for transient response while maintaining reasonably small steady-state current ripple.

Enables lower overall transistor switching frequency if the effective per winding current ripple frequency increase is matched to the original switching frequency. This can reduce switching losses, allowing more power to be handled by the same switches, allowing the switches to run at a lower temperature, or allowing the switches to be made smaller or with less heatsinking, or some combination of these benefits.

Scalability is possible. The nature of activation in combination with the physical construction of various magnetic structures enables arbitrarily increasing numbers of power units to produce further and further ripple reduction benefit while still controlling the same way. Size reduction also occurs when the space around inductors on a PCB is eliminated, as the inductors are combined into one structure.

Ease of manufacturing. One can construct a single core structure with a winding, and then place multiple such cores and windings in a row. Adding more pieces helps reduce ripple in each winding further, and has few if any undesirable effects.

Selecting current ripple reduction. In the invention, the higher the coupling coefficient, the better the current ripple reduction, so long as the coupling coefficient is increased by increasing Lm while holding L_l constant (where coupling coefficient is defined as $k=Lm/(L_l+Lm)$, assuming equal L_l on all phases).

FIG. **12** shows a dual phase, parallel power unit DC-to-DC switching power supply **160** with a composite magnetic core structure **162**. Supply **160** illustrates one specific application of the invention, and includes two windings **164** coupled to switches **166** to alternatively excite the windings and generate an output voltage **168** with reduced current ripple. FIG. **12** also illustrates a "power unit" as sometimes used herein. Specifically, switch **164**A and winding **166**A form one "power unit" and switch **164**B and winding **166**B form another "power unit."

FIG. **13** shows a wheel and spoke core structure **200** constructed according to the invention. Windings **202** couple with separate spokes **204** of structure **200**; though spokes **204** and rim **206** form a continuous core **210**. Structure **200** operates similarly to the ladder structure described above in connection with FIG. **10**, deriving like benefits with windings **202** on spokes as windings **122** on rungs **126**.

FIG. **14** shows a two-ring and column core structure **250** constructed according to the invention. The two rings **252** and columns **254** form a continuous core, with windings **255** wound on columns **254**. Structure **250** operates similarly to the ladder structure described above in connection with FIG. **10**, deriving like benefits with windings **202** on spokes as windings **122** on rungs **126**. As an alternative, rings **252** of structure **250** can be disks or plates (i.e., without an aperture **257**, round or otherwise); those skilled in the art should appreciate that this disk or plate structure is within the scope of the invention.

The invention thus attains the objectives set forth above, among those apparent from the preceding description. Since certain changes may be made in the above methods and systems without departing from the scope of the invention, it is intended that all matter contained in the above description or shown in the accompanying drawing be interpreted as illustrative and not in a limiting sense. For example, those skilled in the art should appreciate that various systems are described herein, including power systems with multiple phases and windings. Typically, each phase has an equal number of windings per turn. Those skilled in the art should thus appreciate that windings with differing numbers of turns can also be included in the various phases of such systems. For example, in accord with the invention, the dc current within each phase may be altered—with the number of turns in the windings also altered—so that the product of NI is the same for each phase.

It is also to be understood by those skilled in the art that the following claims are to cover all generic and specific features of the invention described herein, and all statements of the scope of the invention which, as a matter of language, might be said to fall there between.

Having described the invention, we claim:

1. A DC-to-DC converter for providing an output voltage from an input voltage, comprising first and second inductive windings and a magnetic core cooperatively forming a magnetizing inductance, a first voltage across the first winding being switched at about 180 degrees out of phase with a second voltage across the second winding, to regulate magnitude of the output voltage, the first and second voltages being formed from one or a combination of the input and output voltages, each of the first and second windings having a leakage inductance and being coupled to the magnetic core wherein magnetizing inductance is at least three times greater than the leakage inductance of either winding, the first winding being wound about the core in a first orientation, the second winding being wound about the core in the first orientation.

2. A converter according to claim 1, wherein the input voltage comprises first and second input voltages.

3. A converter according to claim 2, wherein the second input voltage comprises ground, wherein the converter operates as a buck converter.

4. A converter according to claim 1, further comprising one or more transistors for switching the windings out of phase wherein a current per time slope during the time intervals in which current is increasing through the windings is approximately defined by the output voltage divided by the leakage inductance subtracted from one half the input voltage divided by the leakage inductance.

5. A converter according to claim 1, wherein the windings and core are constructed and arranged to substantially maximize coupling between windings by maintaining the leakage inductance at a substantially constant level while increasing the magnetizing inductance.

6. A converter according to claim 1, wherein the core comprises first and second substantially parallel core elements, the first winding being wound about the first core element the first orientation, the second winding being wound about the second core element in the first orientation.

7. A converter according to claim 6, further comprising one or more connecting elements rigidly coupling the first and second parallel core elements together.

8. A converter according to claim 1, wherein the core comprises one of a gapped high-permeability element and a low-permeability element, to serve as a leakage path structure to carry at least part of a leakage flux, the leakage flux being defined as a flux present when each of the windings has an equal DC current.

9. A converter according to claim 8, wherein the leakage path structure comprises a core leg or shunt.

10. A converter according to claim 1, further comprising circuitry to activate one or more of the windings at a selected duty cycle.

11. A converter according to claim 10, wherein the duty cycle comprises a duty cycle between about 5% and 90%.

12. A converter according to claim 10, wherein the duty cycle is about 50%.

13. A converter according to claim 1, further comprising circuitry to alternatively activate each of the windings at about 50% duty cycle.

14. A converter according to claim 1, wherein one end of each of the windings is switched between the input voltage and ground.

15. A converter according to claim 1, wherein the first and second windings have an equal number of turns in the windings.

16. A converter according to claim 1, wherein the first winding has a first number of turns and the second winding

has a second number of turns, the first number being different from the second number, and wherein a NI product for each of the first and second windings is substantially equal.

17. A method for reducing ripple in a DC-to-DC converter of the type producing an output voltage from an input voltage, comprising the steps of:

orienting, in like direction, first and second windings about a common core to increase coupling between the windings; and

alternatively activating each winding about 180 degrees out of phase with the second winding, to regulate magnitude of the output voltage.

18. A method of claim 17, further comprising switching the voltages across the windings by connecting one end of each winding to a common output voltage, and individually switching the other end of each winding between ground and an input voltage.

19. The method of claim 17, further comprising the step of forming the core with two substantially parallel core elements, wherein the step of orienting comprises orienting each of the windings on a separate core element.

20. The method of claim 17, further comprising the step of activating one or more of the windings at a selected duty cycle.

21. The method of claim 20, wherein the step of activating comprises activating the windings at a duty cycle between about 5% and 90%.

22. The method of claim 20, wherein the step of activating comprises activating the windings at a duty cycle at about 50%.

23. The method of claim 17, further comprising the steps of forming a first number of turns in the first winding and a second number of turns in the second winding.

24. The method of claim 23, wherein the first number is different from the second number, and further comprising the steps of applying a first current through the first winding and applying a second current through the second winding, the first current being different from the second current, wherein a NI product for each of the first and second windings is substantially equal.

25. A DC to DC converter for providing an output voltage from one or more input voltages, comprising (a) a common magnetic core and (b) N inductive windings alternatively switched, at one end, to regulate magnitude of the output voltage, each of the windings having a turn-on switching transition separated in switching phase by at least about 360/N degrees from any other of the windings, each of the windings having a turn-off switching transition separated in phase by at least about 360/N degrees from any other of the windings, each of the N windings being wound about the core in like orientation, N being an integer greater than or equal to three.

26. A converter of claim 25, wherein each of the windings comprises a leakage inductance, each of the windings being coupled the common magnetic core wherein magnetizing inductance defined by magnetic interaction between the windings is greater than about three times the leakage inductance of any one of the windings.

27. A converter according to claim 26, further comprising one or more transistors for switching the windings out of phase wherein a current per time slope during the time intervals in which current is increasing through the windings is approximately defined by the output voltage divided by the leakage inductance subtracted from the input voltage divided by the leakage inductance divided by N.

28. A converter according to claim 26, wherein the windings and core are constructed and arranged to substan-

tially maximize coupling between windings by maintaining the leakage inductance at a substantially constant level while increasing the magnetizing inductance.

29. A converter according to claim **26**, wherein one or more of the windings comprise a gapped high permeability element to carry at least part of a leakage flux, the leakage flux being defined as a flux present when each of the windings has an equal DC current.

30. A converter of claim **25**, wherein the core comprises a wheel and spoke configuration, and wherein each of the windings are wound about separate spokes of the configuration.

31. A converter of claim **25**, wherein the core structure comprises a two-plate and multiple column configuration, and wherein each of the windings are wound about separate columns of the configuration.

32. A converter of claim **25**, wherein the core structure comprises a two-ring and multiple column configuration, and wherein each of the windings are wound about separate columns of the configuration.

33. A converter according to claim **25**, wherein the input voltages comprise first and second input voltages, the second input voltage comprising ground, wherein the converter operates as a buck converter.

34. A converter according to claim **25**, wherein the core comprises N substantially parallel core elements, the N winding being wound about the N core elements in a same orientation.

35. A converter according to claim **34**, further comprising one or more connecting elements rigidly coupling adjacent N parallel core elements together.

36. A converter according to claim **25**, further comprising circuitry to activate one or more of the windings at a selected duty cycle.

37. A converter according to claim **36**, wherein the duty cycle comprises a duty cycle between about 5% and 90%.

38. A converter according to claim **37**, wherein the duty cycle is about 50%.

39. A converter according to claim **25**, wherein each of the N inductive windings comprises an equal number of turns.

40. A converter according to claim **25**, wherein at least one of the N inductive windings comprises a different number of turns from at least one other of the N windings.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,362,986 B1 | Page 1 of 1
DATED : March 26, 2002
INVENTOR(S) : Aaron M. Schultz and Charles R. Sullivan

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 14,
Line 5, should read as follows:
-- 17. A method for reducing ripple in a DC-to-DC converter of the type producing an output voltage from an input voltage, comprising the steps of:

orienting, in like direction, first and second windings about a common core to increase coupling between the windings; and

alternatively activating [each] the first winding about 180 degrees out of phase with the second winding, to regulate magnitude of the output voltage. --

Signed and Sealed this

Sixteenth Day of July, 2002

Attest:

JAMES E. ROGAN

Attesting Officer | *Director of the United States Patent and Trademark Office*

EXHIBIT 9

US007525408B1

(12) **United States Patent**
Li et al.

(10) **Patent No.: US 7,525,408 B1**
(45) **Date of Patent: Apr. 28, 2009**

(54) **METHOD FOR MAKING MAGNETIC COMPONENTS WITH N-PHASE COUPLING, AND RELATED INDUCTOR STRUCTURES**

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(73) Assignee: **Volterra Semiconductor Corporation**, Fremont, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 130 days.

(21) Appl. No.: **11/852,226**

(22) Filed: **Sep. 7, 2007**

Related U.S. Application Data

(62) Division of application No. 10/318,896, filed on Dec. 13, 2002, now Pat. No. 7,352,269.

(51) **Int. Cl.**
H01F 5/00 (2006.01)

(52) **U.S. Cl.** **336/200**

(58) **Field of Classification Search** 336/65, 336/83, 183, 200, 220–222, 232
See application file for complete search history.

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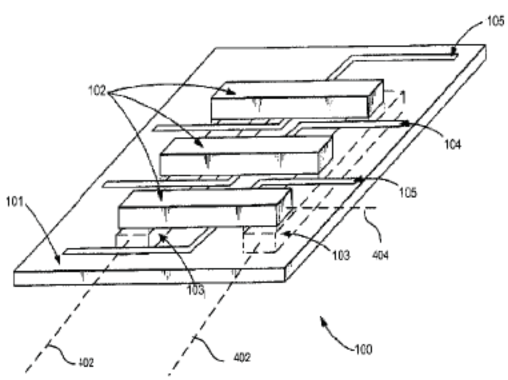
(57) **ABSTRACT**

Methods and structures for constructing a magnetic core of a coupled inductor. The method provides for constructing N-phase coupled inductors as both single and scalable magnetic structures, where N is an integer greater than 1. The method additionally describes how such a construction of the magnetic core may enhance the benefits of using the scalable N-phase coupled inductor. The first and second magnetic cores may be formed into shapes that, when coupled together, may form a single scalable magnetic core. For example, the cores can be fashioned into shapes such as a U, an I, an H, a ring, a rectangle, and a comb, that cooperatively form the single magnetic core.

20 Claims, 13 Drawing Sheets



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* cited by examiner

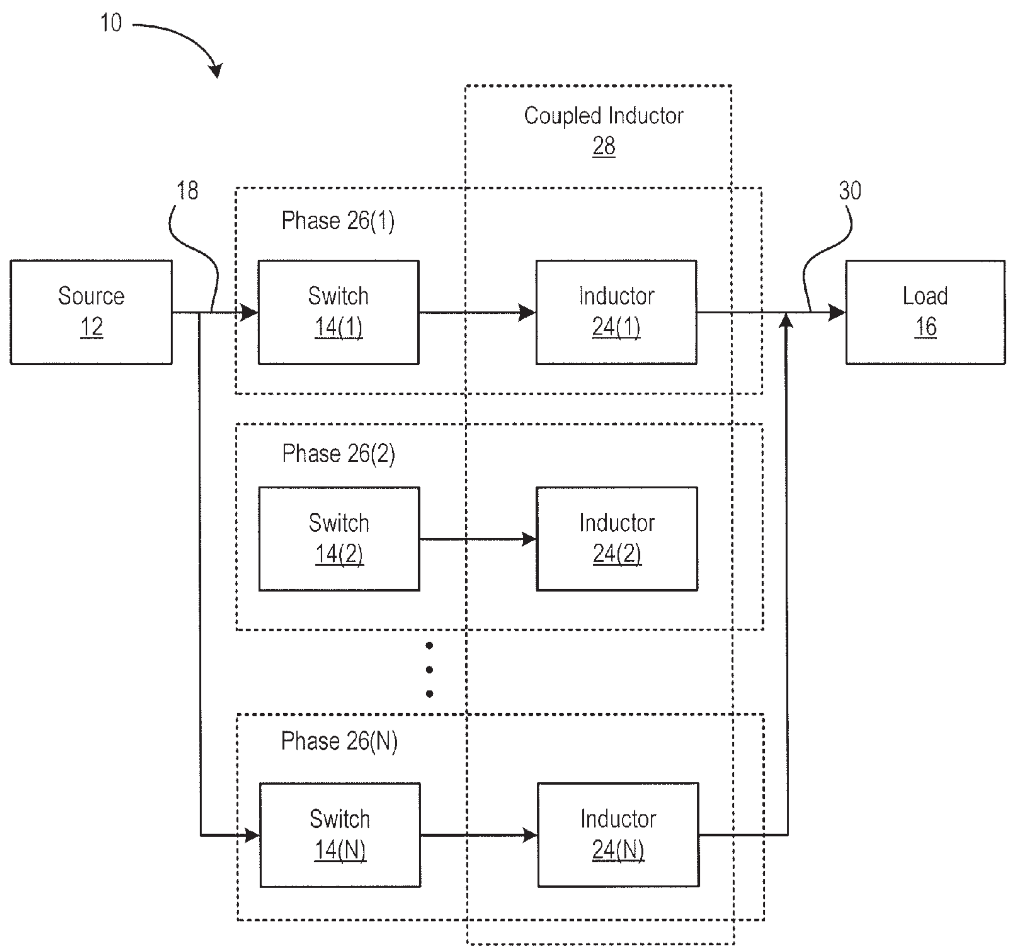

10
Coupled Inductor
28
18
30
Phase 26(1)
Source
12
Switch
14(1)
Inductor
24(1)
Load
16
Phase 26(2)
Switch
14(2)
Inductor
24(2)
Phase 26(N)
Switch
14(N)
Inductor
24(N)

FIG. 1

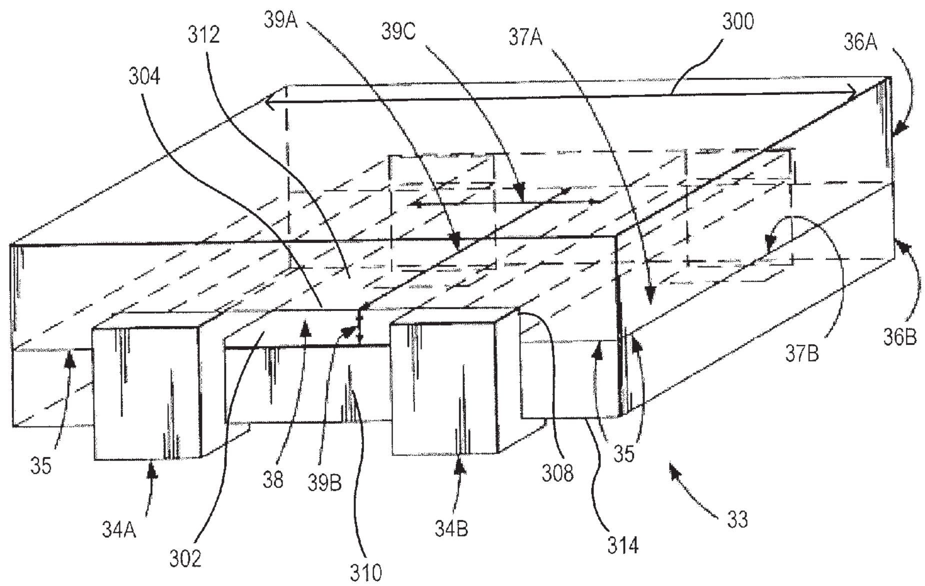

39A
312
39C
37A
300
36A
304
37B
36B
35
38
39B
308
35
33
34A
34B
314
302
310

FIG. 2

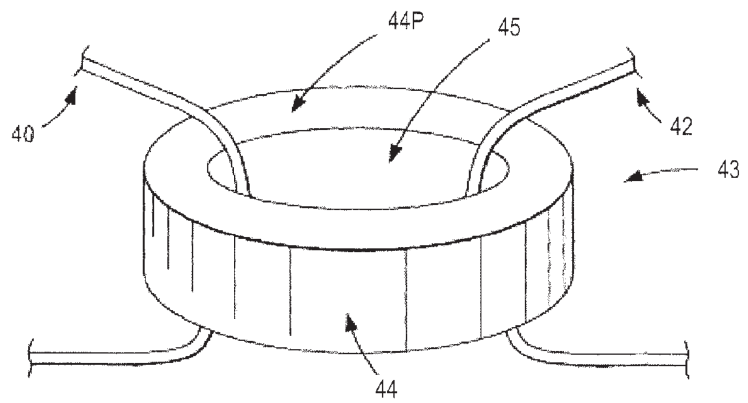

44P
45
40
42
43
44

FIG. 3

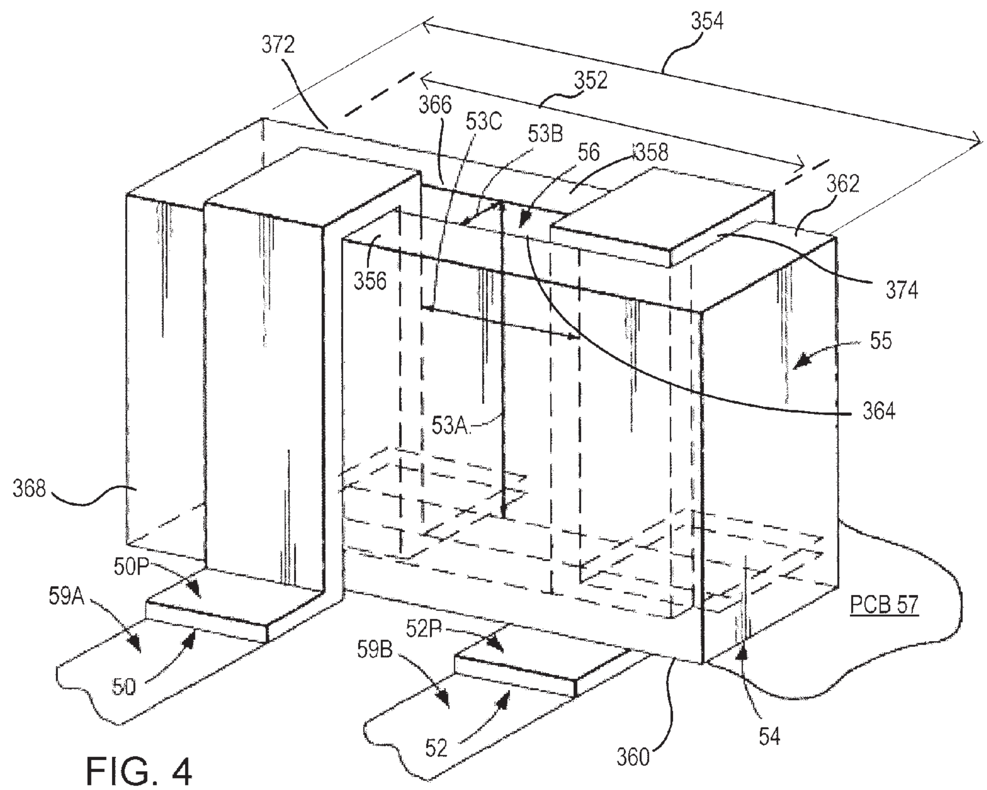

372
354
352
366
53C
53B
56
358
362
374
356
55
364
53A
368
50P
59A
52P
59B
50
52
360
54
PCB 57

FIG. 4

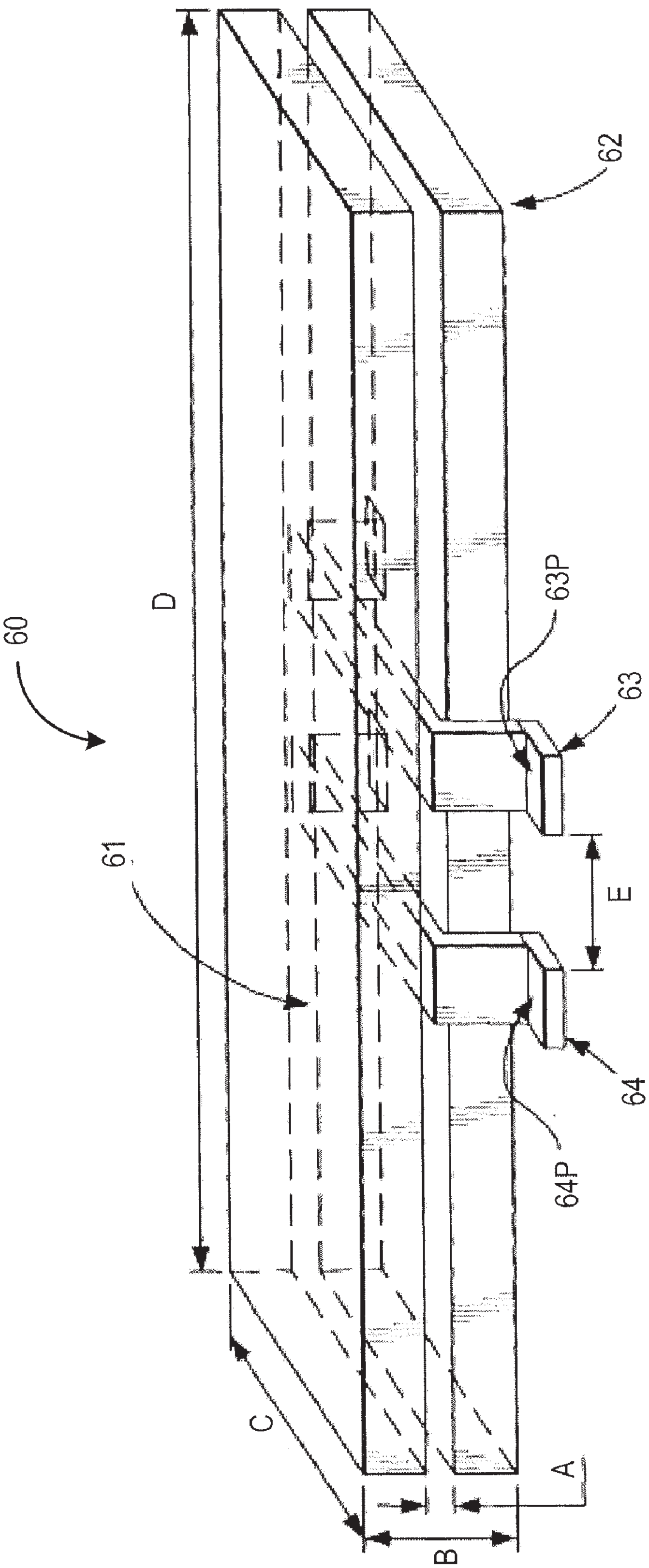


FIG. 5

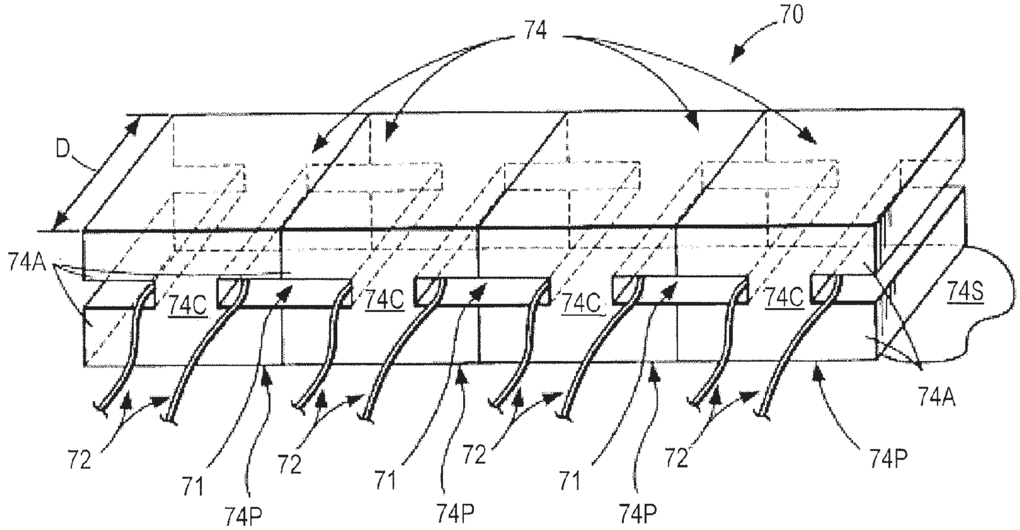

74
70
D
74A
74C
74C
74C
74C
74C
74S
74A
72
71
74P
72
71
74P
72
71
74P
72
74P

FIG. 6

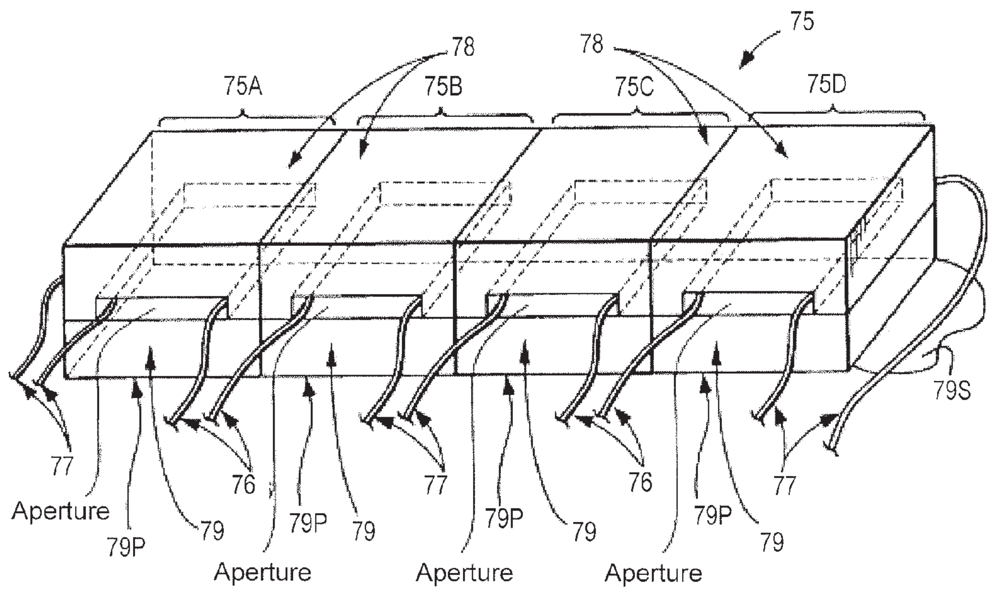
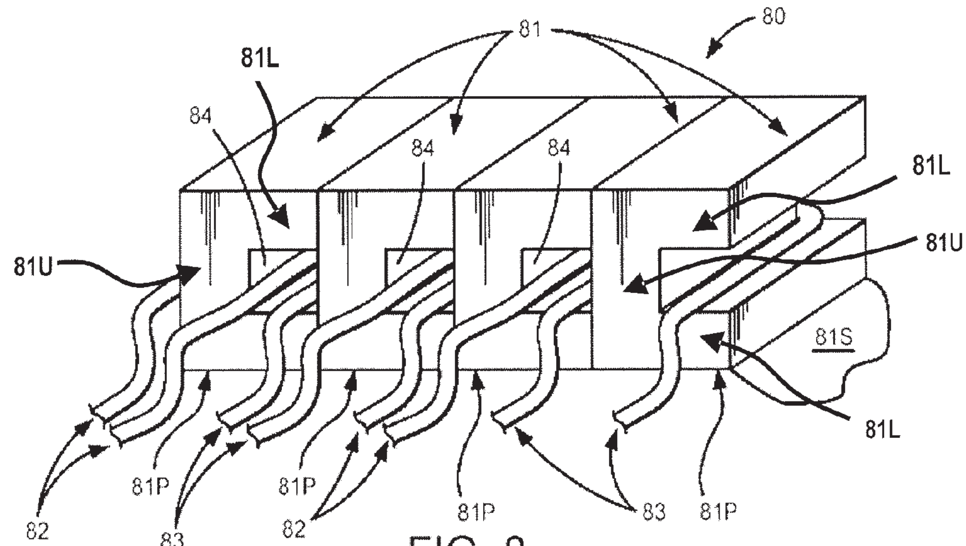
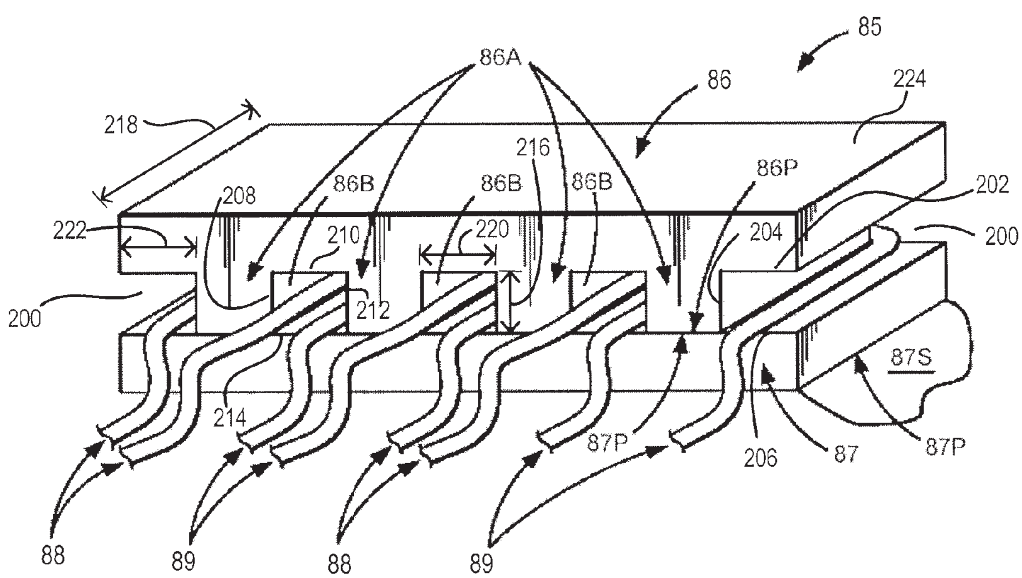

75
78
78
75A
75B
75C
75D
79S
77
Aperture
79P
76
79
79P
79
Aperture
77
79P
79
Aperture
76
79P
79
Aperture
77

FIG. 7



80
81
81L
84
84
84
81L
81U
81U
81S
81L
82
81P
83
81P
82
81P
83
81P

FIG. 8



85
86A
86
224
218
216
86P
208
86B
86B
86B
202
222
210
220
204
200
200
212
87S
214
87P
206
87
87P
88
89
88
89

FIG. 9

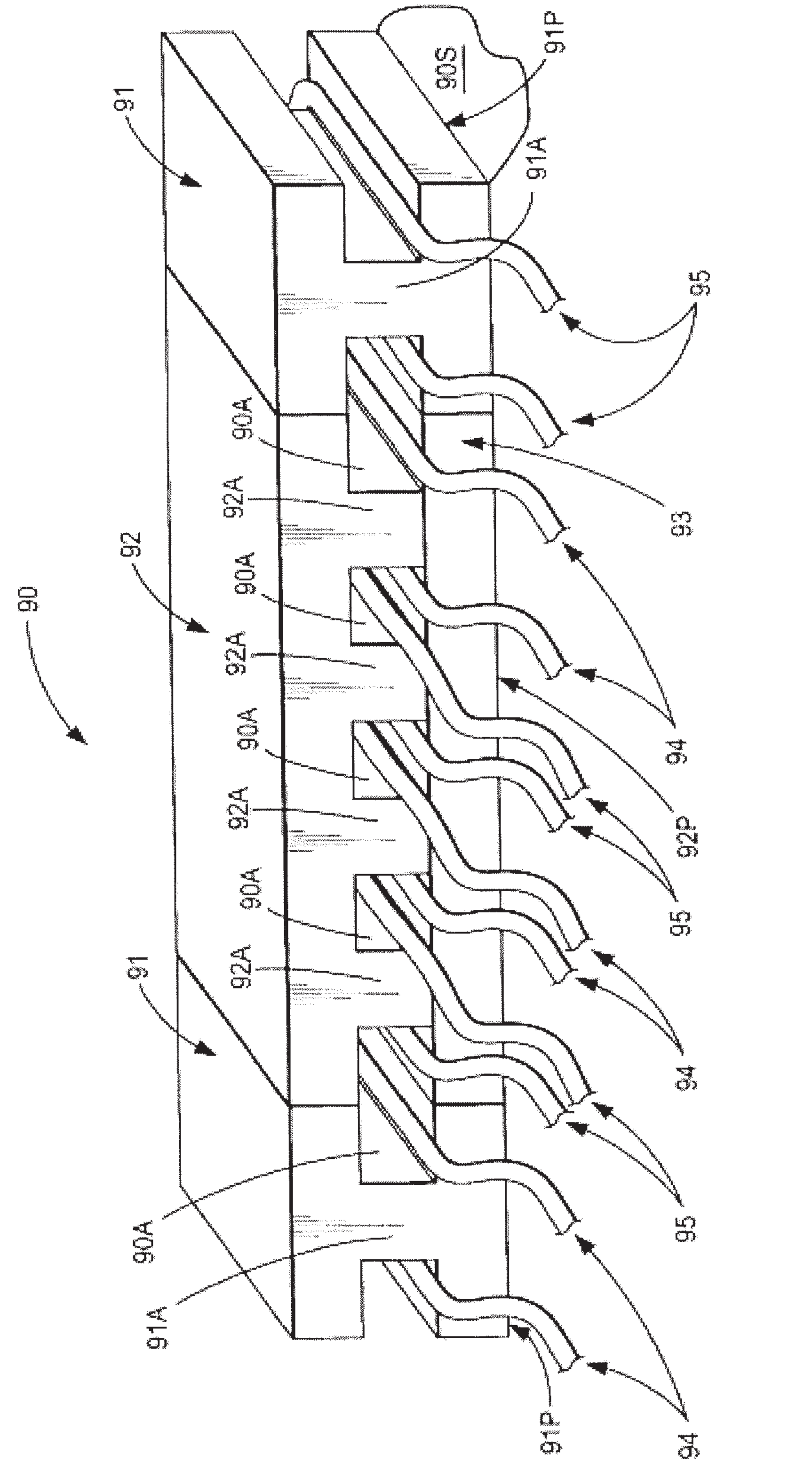


FIG. 10

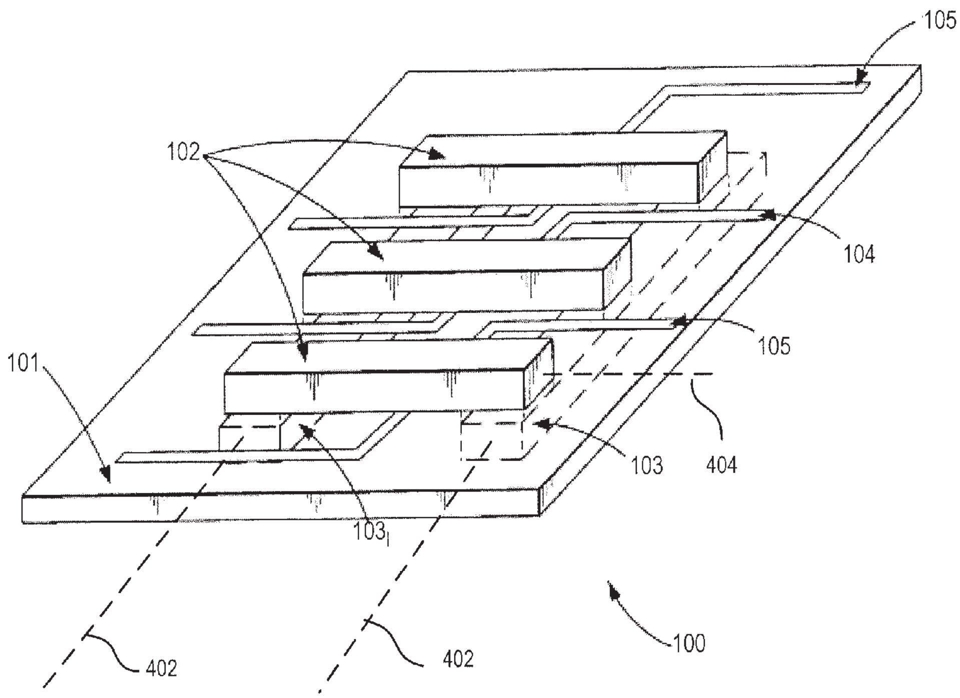


FIG. 11

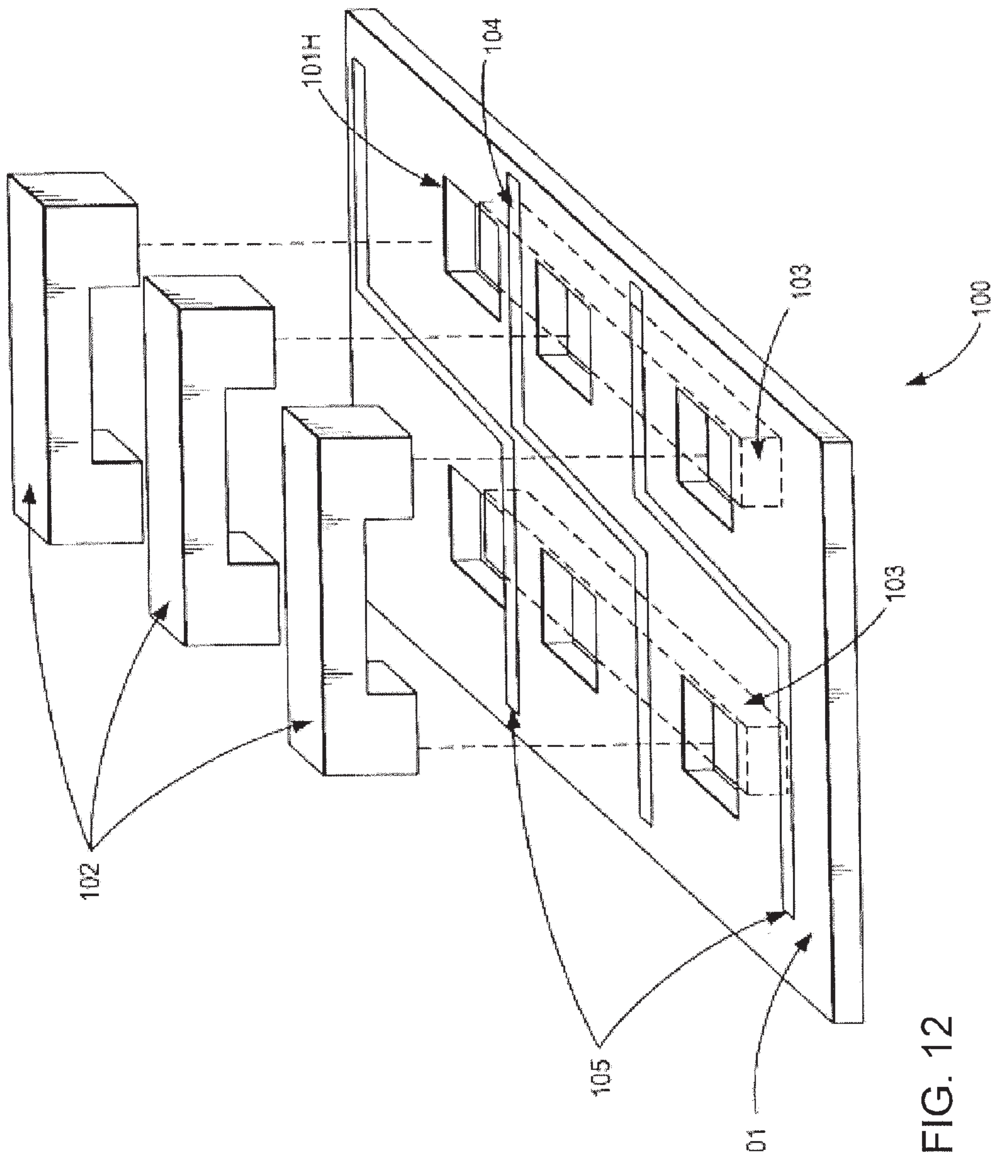


FIG. 12

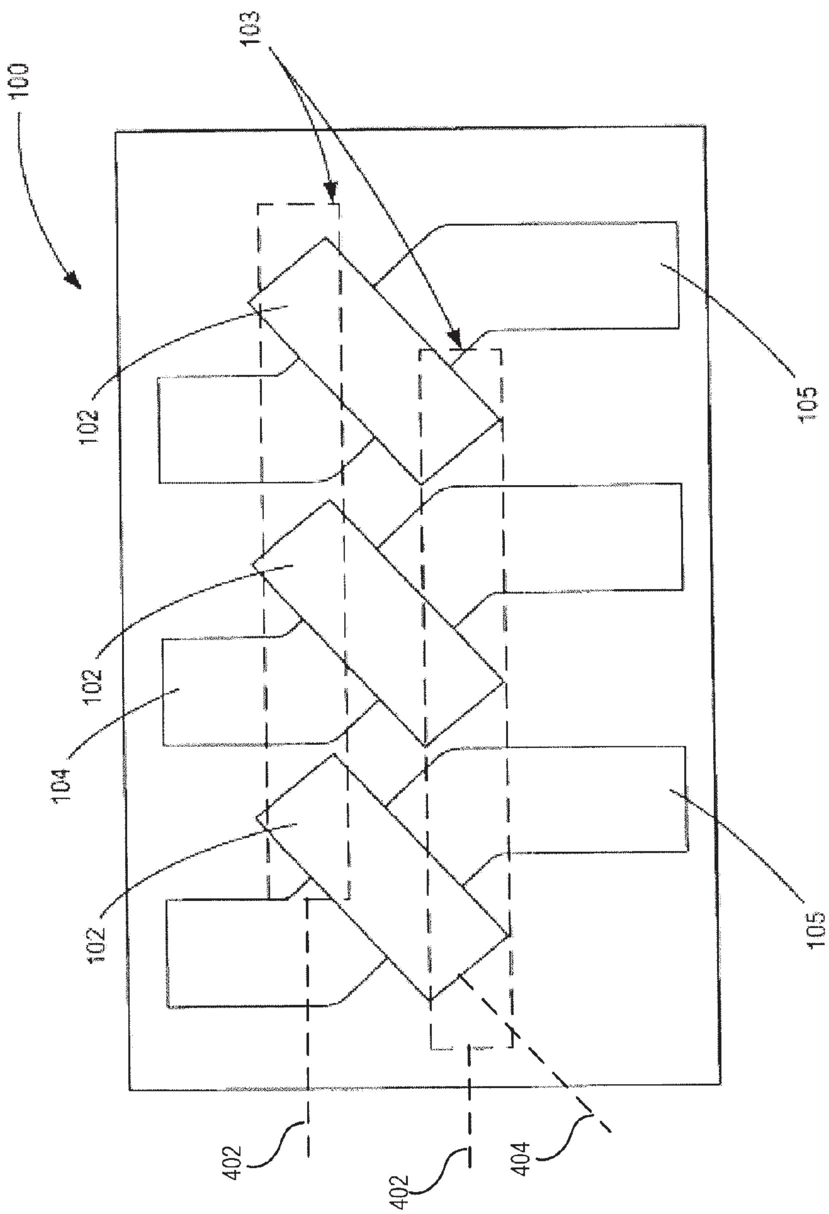
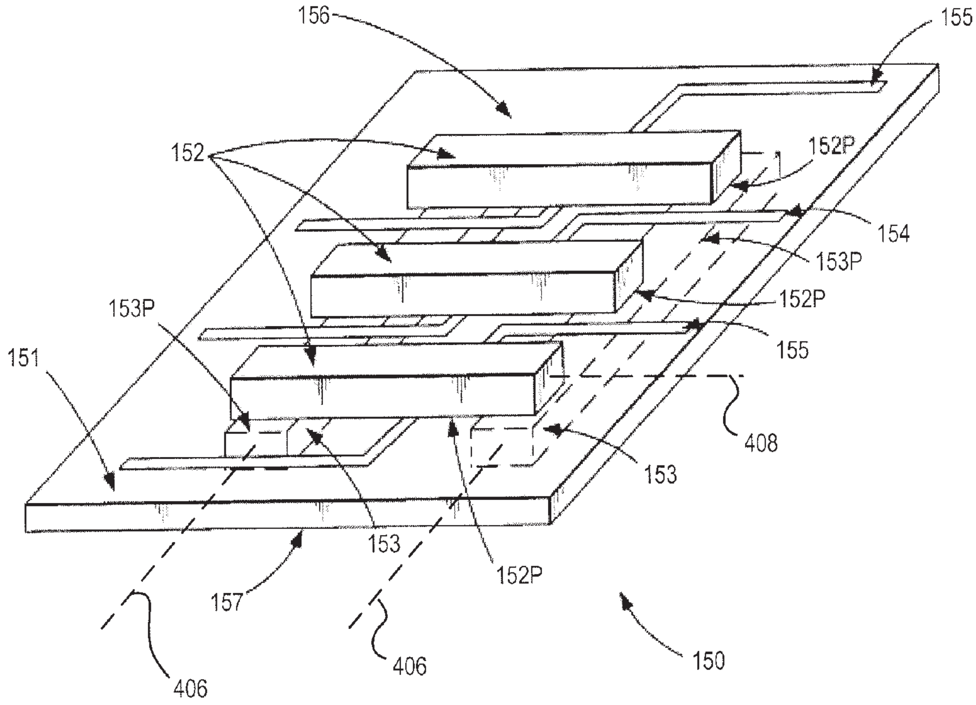


FIG. 13



156
155
152
152P
154
153P
152P
153P
155
151
408
153
153
152P
157
406
406
150

FIG. 14

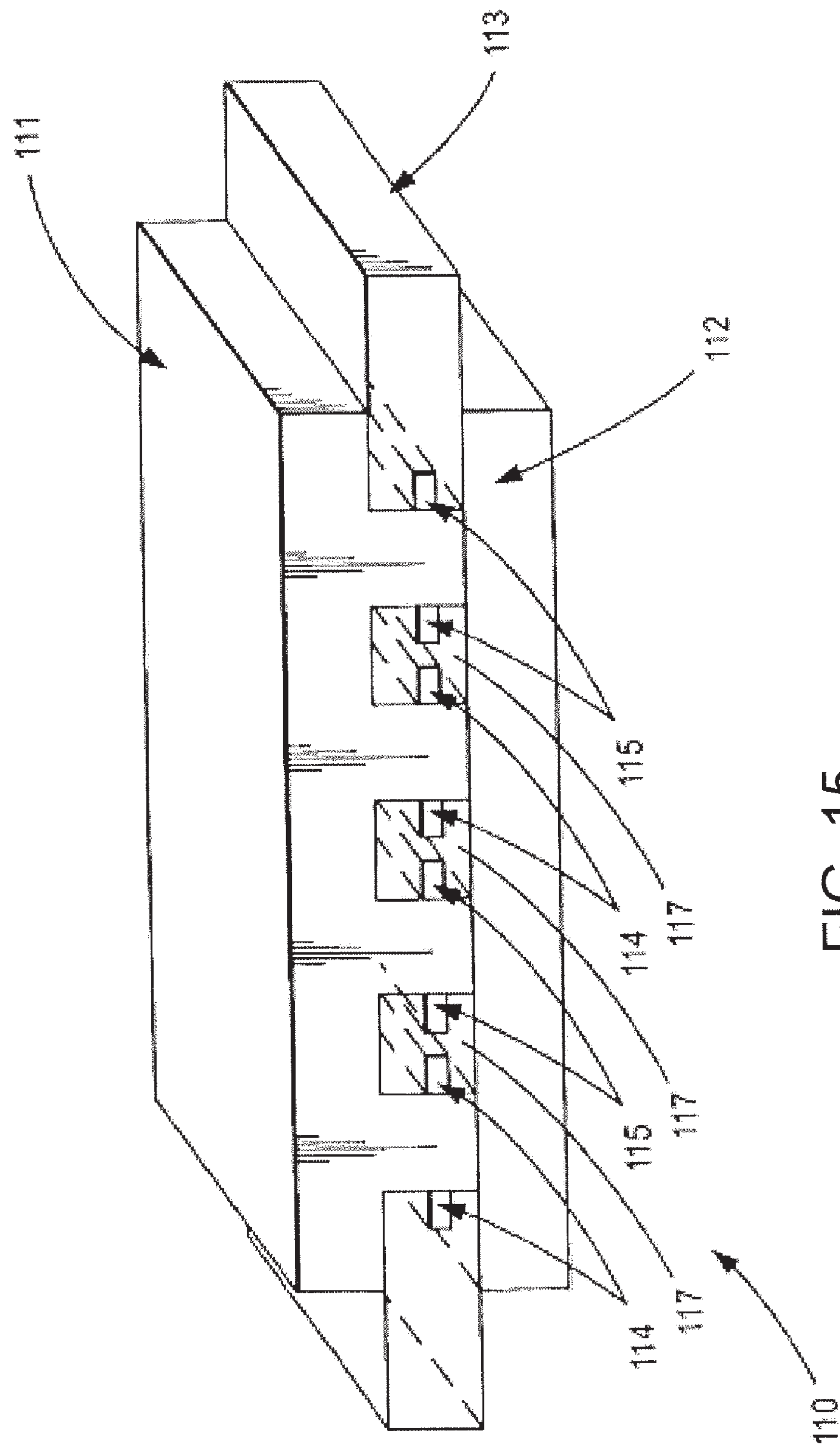


FIG. 15

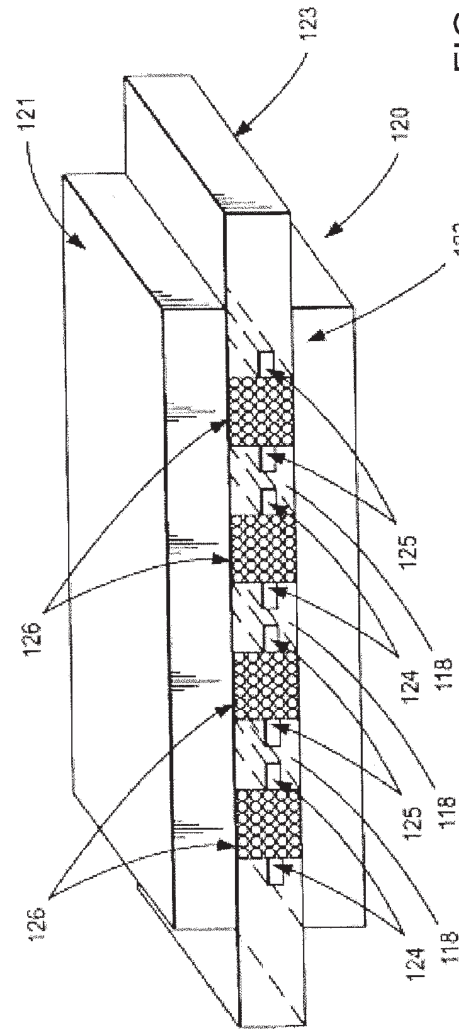

121
123
120
122
126
125
124
118
125
118
126
124
118

FIG. 16

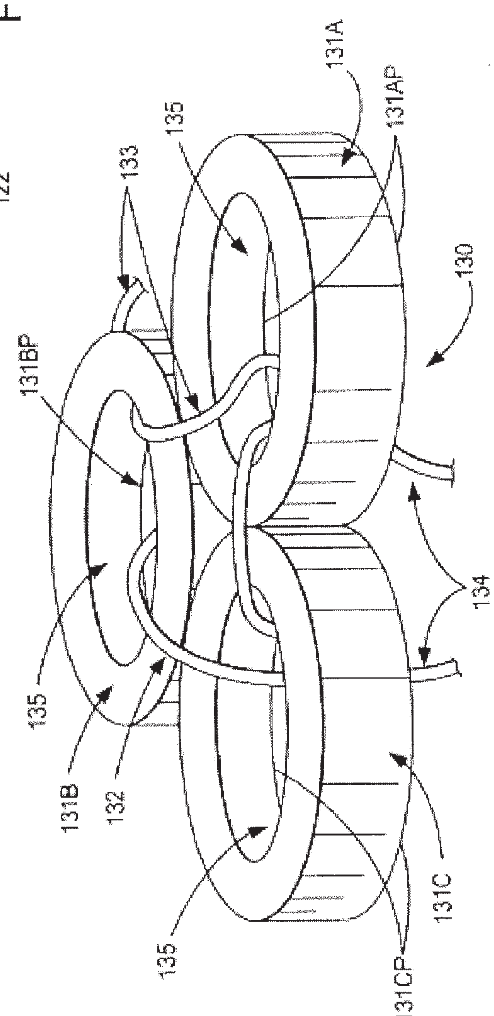

133
135
131A
131AP
130
131BP
134
135
131B
132
135
131C
131CP

FIG. 17

METHOD FOR MAKING MAGNETIC COMPONENTS WITH N-PHASE COUPLING, AND RELATED INDUCTOR STRUCTURES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a divisional of U.S. patent application Ser. No. 10/318,896, filed 13 Dec. 2002, which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates generally to making DC-to-DC converters. More specifically the invention relates to construction of a coupled inductor within a multi-phase DC-to-DC converter.

2. Background of the Invention

A DC-to-DC converter, as known in the art, provides an output voltage that is a step-up, a step-down, or a polarity reversal of the input voltage source. Certain known DC-to-DC converters have parallel power units with inputs coupled to a common DC voltage source and outputs coupled to a load, such as a microprocessor. Multiple power-units can sometimes reduce cost by lowering the power and size rating of components. A further benefit is that multiple power units provide smaller per-power-unit peak current levels, combined with smaller passive components.

The prior art also includes switching techniques in parallel-power-unit DC-to-DC converters. By way of example, power units may be switched with pulse width modulation (PWM) or with pulse frequency modulation (PFM). Typically, in a parallel-unit buck converter, the energizing and de-energizing of the inductance in each power unit occurs out of phase with switches coupled to the input, inductor and ground. Additional performance benefits are provided when the switches of one power unit, coupling the inductors to the DC input voltage or to ground, are out of phase with respect to the switches in another power unit. Such a "multi-phase," parallel power unit technique results in ripple current cancellation at a capacitor, to which all the inductors are coupled at their respective output terminals.

It is clear that smaller inductances are needed in DC-to-DC converters to support the response time required in load transients and without prohibitively costly output capacitance. More particularly, the capacitance requirements for systems with fast loads, and large inductors, may make it impossible to provide adequate capacitance configurations, in part due to the parasitic inductance generated by a large physical layout. But smaller inductors create other issues, such as the higher frequencies used in bounding the AC peak-to-peak current ripple within each power unit. Higher frequencies and smaller inductances enable shrinking of part size and weight. However, higher switching frequencies result in more heat dissipation and lower efficiency. In short, small inductance is good for transient response, but large inductance is good for AC current ripple reduction and efficiency.

The prior art has sought to reduce the current ripple in multiphase switching topologies by coupling inductors. For example, one system set forth in U.S. Pat. No. 5,204,809, incorporated herein by reference, couples two inductors in a dual-phase system driven by an H bridge to help reduce ripple current. In one article, *Investigating Coupling Inductors in the Interleaving QSW VRM, IEEE APEC* (Wong, February 2000), slight benefit is shown in ripple reduction by coupling two windings using presently available magnetic core shapes.

However, the benefit from this method is limited in that it only offers slight reduction in ripple at some duty cycles for limited amounts of coupling.

One known DC-to-DC converter offers improved ripple reduction that either reduces or eliminates the afore-mentioned difficulties. Such a DC-to-DC converter is described in commonly owned U.S. Pat. No. 6,362,986 issued to Schultz et al., incorporated herein by reference. The '986 patent can improve converter efficiency and reduce the cost of manufacturing DC-to-DC converters.

Specifically, the '986 patent shows one system that reduces the ripple of the inductor current in a two-phase coupled inductor within a DC-to-DC buck converter. The '986 patent also provides a multi-phase transformer model to illustrate the working principles of multi-phase coupled inductors. It is a continuing problem to address scalability and implementation issues DC-to-DC converters.

As circuit components and, thus, printed circuit boards (PCB), become smaller due to technology advancements, smaller and more scalable DC-to-DC converters are needed to provide for a variety of voltage conversion needs. One specific feature presented hereinafter is to provide a DC-to-DC converter, the DC-to-DC converter being scalable in some embodiments. Another feature is to provide a converter that is mountable to a PCB. Yet another feature is to provide a lower cost manufacturing methodology for DC-to-DC converters, as compared to the prior art. These and other features will be apparent in the description that follows.

SUMMARY OF THE INVENTION

As used herein, a "coupled" inductor implies an interaction between multiple inductors of different phases. Coupled inductors described herein may be used within DC-to-DC converters or within a power converter for power conversion applications, for example.

A method of one aspect provides for constructing a magnetic core. Such a core is, for example, useful in applications detailed in the '986 patent. In one aspect, the method provides for constructing N-phase coupled inductors as both single and scalable magnetic structures, where N is greater than 1. An N-phase inductor as described herein may include N-number of windings. One method additionally describes construction of a magnetic core that enhances the benefits of using the scalable N-phase coupled inductor.

In one aspect, the N-phase coupled inductor is formed by coupling first and second magnetic cores in such a way that a planar surface of the first core is substantially aligned with a planar surface of the second core in a common plane. The first and second magnetic cores may be formed into shapes that, when coupled together, may form a single scalable magnetic core having desirable characteristics, such as ripple current reduction and ease of implementation. In one example, the cores are fashioned into shapes, such as a U-shape, an I-shape (e.g., a bar), an H-shape, a ring-shape, a rectangular-shape, or a comb. In another example, the cores could be fashioned into a printed circuit trace within a PCB.

In another aspect, certain cores form passageways through which conductive windings are wound when coupled together. Other cores may already form these passageways (e.g., the ring-shaped core and the rectangularly shaped core). For example, two H-shaped magnetic cores may be coupled at the legs of each magnetic core to form a passageway. As another example, a multi-leg core may be formed as a comb-shaped core coupled to an I-shaped core. In yet another example, two I-shaped cores are layered about a PCB such that passageways are formed when the two cores are coupled

to one another at two or more places, or when pre-configured holes in the PCB are filled with a ferromagnetic powder.

Advantages of the method and structures herein include a scalable and cost effective DC-to-DC converter that reduces or nearly eliminates ripple current. The methods and structures further techniques that achieve the benefit of various performance characteristics with a single, scalable, topology.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows one multi-phase DC-to-DC converter system;

FIG. **2** shows one two-phase coupled inductor;

FIG. **3** shows one two-phase coupled ring-core inductor;

FIG. **4** shows one vertically mounted two-phase coupled inductor;

FIG. **5** shows one plate structured two-phase coupled inductor;

FIG. **6** shows one scalable multi-phase coupled inductor with H-shaped cores;

FIG. **7** shows one scalable multi-phase coupled inductor with rectangular-shaped cores;

FIG. **8** shows one scalable multi-phase coupled inductor with U-shaped cores;

FIG. **9** shows one integrated multi-phase coupled inductor with a comb-shaped core;

FIG. **10** shows one scalable multi-phase coupled inductor with combinations of shaped cores;

FIG. **11** shows one scalable multi-phase coupled inductor with "staple" cores;

FIG. **12** shows an assembly view of the coupled inductor of FIG. **11**;

FIG. **13** shows a surface view of the inductor of FIG. **11**;

FIG. **14** shows one scaleable coupled inductor with bar magnet cores;

FIG. **15** shows one multi-phase coupled inductor with through-board integration;

FIG. **16** shows another multi-phase coupled inductor with through-board integration; and

FIG. **17** shows one scalable multi-phase coupled ring-core inductor.

DETAILED DESCRIPTION OF THE DRAWINGS

FIG. **1** shows a multi-phase DC-to-DC converter system **10**. System **10** includes a power source **12** electrically coupled with N switches **14** and N inductors **24**, with N=2, for supplying power to a load **16**. Each switch and inductor pair **14**, **24** represent one phase **26** of system **10**, as shown. Inductors **24** cooperate together as a coupled inductor **28**. Power source **12** may, for example, be either a DC power source, such as a battery, or an AC power source cooperatively coupled to a rectifier, such as a bridge rectifier, to provide DC power in signal **18**. Each switch **14** may include a plurality of switches to perform the functions of DC-to-DC converter system **10**.

In operation, DC-to-DC converter system **10** converts an input signal **18** from source **12** to an output signal **30**. The voltage of signal **30** may be controlled through operation of switches **14**, to be equal to or different from signal **18**. Specifically, coupled inductor **28** has one or more windings (not shown) that extend through and about inductors **24**, as described in detail below. These windings attach to switches **14**, which collectively operate to regulate the output voltage of signal **30** by sequentially switching inductors **24** to signal **18**.

When N=2, system **10** may for example be used as a two-phase power converter, (e.g., power supply). System **10** may also be used in both DC and AC based power supplies to replace a plurality of individual discrete inductors such that coupled inductor **28** reduces inductor ripple current, filter capacitances, and/or PCB footprint sizes, while delivering higher system efficiency and enhanced system reliability. Other functional and operational aspects of DC-to-DC converter system **10** may be exemplarily described in the '986 patent, features of coupled inductor **28** are described in detail below in connection with FIG. **2**-FIG. **17**. Those skilled in the art appreciate that system **10** may be arranged with different topologies to provide a coupled inductor **28** and without departing from the scope hereof.

FIG. **2** shows a two-phase coupled inductor **33**, in accord with one embodiment. Inductor **33** may, for example, serve as inductor **28** of FIG. **1**, with N=2. The two-phase coupled inductor **33** may include a first magnetic core **36**A and a second magnetic core **36**B. The first and second magnetic cores **36**A, **36**B, respectively, are coupled together such that planar surfaces **37**A, **37**B, respectively, of each core are substantially aligned in a common plane, represented by line **35**. When the two magnetic cores **36**A and **36**B are coupled together, they cooperatively form a single magnetic core for use as a two-phase coupled inductor **33**.

In this embodiment, the first magnetic core **36**A may be formed from a ferromagnetic material into a U-shape. The second magnetic core **36**B may be formed from the same ferromagnetic material into a bar, or I-shape, as shown. As the two magnetic cores **36**A, **36**B are coupled together, they form a passageway **38** through which windings **34**A, **34**B are wound. The windings **34**A, **34**B may be formed of a conductive material, such as copper, that wind though and about the passageway **38** and the magnetic core **36**B. Moreover, those skilled in art should appreciate that windings **34**A, **34**B may include a same or differing number of turns about the magnetic core **36**B. Windings **34**A, **34**B are shown as single turn windings, to decrease resistance through inductor **33**.

The windings **34**A and **34**B of inductor **33** may be wound in the same or different orientation from one another. The windings **34**A and **34**B may also be either wound about the single magnetic core in the same number of turns or in a different number of turns. The number of turns and orientation of each winding may be selected so as to support the functionality of the '986 patent, for example. By orienting the windings **34**A and **34**B in the same direction, the coupling is directed so as to reduce the ripple current flowing in windings **34**A, **34**B.

Those skilled in the art should appreciate that a gap (not shown) may exist between magnetic cores **36**A, **36**B, for example to reduce the sensitivity to direct current when inductor **33** is used within a switching power converter. Such a gap is for example illustratively discussed as dimension A, FIG. **5**.

The dimensional distance between windings **34**A, **34**B may also be adjusted to adjust leakage inductance. Such a dimension is illustratively discussed as dimension E, FIG. **5**.

As shown, magnetic core **36**A is a "U-shaped" core while magnetic core **36**B is an unshaped flat plate. Those skilled in the art should also appreciate that coupled inductor **33** may be formed with magnetic cores with different shapes. By way of example, two "L-shaped" or two "U-shaped" cores may be coupled together to provide like overall form as combined cores **36**A, **36**B, to provide like functionality within a switching power converter. Cores **36**A, **36**B may be similarly replaced with a solid magnetic core block with a hole therein to form passageway **38**. At least part of passageway **38** is free

from intervening magnetic structure between windings **34**A, **34**B; air or non-magnetic structure may for example fill the space of passageway **38** and between the windings **34**A, **34**B. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **34**A, **34**B, and within passageway **38**; by way of example, the cross-sectional area of passageway **38** may be defined by the plane of dimensions **39**A (depth), **39**B (height), which is perpendicular to a line **39**C (separation distance) between windings **34**A, **34**B.

FIG. **2** also illustrates one advantageous feature associated with windings **34**A, **34**B. Specifically, each of windings **34**A, **34**B is shown with a rectangular cross-section that, when folded underneath core **36**B, as shown, produces a tab for soldering to a PCB, and without the need for a separate item. Other windings discussed below may have similar beneficial features.

FIG. **2** also shows planar surfaces **302**, **304**, **308**, and **314**, legs or sides **310** and **312**, and width **300**.

FIG. **3** shows a single two-phase ring-core coupled inductor **43**, in accord with one embodiment. Inductor **43** may be combined with other embodiments herein, for example, to serve as inductor **28** of FIG. **1**. The ring-core inductor **43** is formed from a ring magnetic core **44**. The core **44** has a passageway **45**; windings **40** and **42** are wound through passageway **45** and about the core **44**, as shown. In this embodiment, core **44** is formed as a single magnetic core; however multiple magnetic cores, such as two semi-circles, may be cooperatively combined to form a similar core structure. Other single magnetic core embodiments shown herein may also be formed by cooperatively combining multiple magnetic cores as discussed in FIG. **17**. Such a combination may align plane **44**P of magnetic core **44** in the same plane of other magnetic cores **44**, for example to facilitate mounting to a PCB. At least part of passageway **45** is free from intervening magnetic structure between windings **40**, **42**; air may for example fill the space of passageway **45** and between windings **40**, **42**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **40**, **42**, and within passageway **45**.

In one embodiment, windings **40**, **42** wind through passageway **45** and around ring magnetic core **44** such that ring magnetic core **44** and windings **40**, **42** cooperate with two phase coupling within a switching power converter. Winding **40** is oriented such dc current in winding **40** flows in a first direction within passageway **45**; winding **42** is oriented such that dc current in winding **42** flows in a second direction within passageway **45**, where the first direction is opposite to the second direction. Such a configuration avoids dc saturation of core **44**, and effectively reduces ripple current. See U.S. Pat. No. 6,362,986.

FIG. **4** shows a vertically mounted two-phase coupled inductor **54**, in accord with one embodiment. Inductor **54** may be combined and/or formed with other embodiments herein, for example, to serve as inductor **28** of FIG. **1**. The inductor **54** is formed as a rectangular-shaped magnetic core **55**. The core **55** forms a passageway **56**; windings **50** and **52** may be wound through passageway **56** and about the core **55**. In this embodiment, the inductor **54** may be vertically mounted on a plane of PCB **57** (e.g., one end of passageway **56** faces the plane of the PCB **57**) so as to minimize a “footprint”, or real estate, occupied by the inductor **54** on the PCB **57**. This embodiment may improve board layout convenience. Windings **50** and **52** may connect to printed traces **59**A, **59**B on the PCB **57** for receiving current. Additionally, windings **50** and **52** may be used to mount inductor **54** to the PCB **57**, such as by flat portions **50**P, **52**P of respective windings **50**, **52**. Specifically, portions **50**P, **52**P may be soldered underneath to PCB **57**. At least part of passageway **56** is free from intervening magnetic structure between windings **50**, **52**; air may for example fill the space of passageway **56** and between windings **50**, **52**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **50**, **52**, and within passageway **56**; by way of example, the cross-sectional area of passageway **56** may be defined by the plane of dimensions **53**A (height), **53**B (depth), which is perpendicular to a line **53**C (separation distance) between windings **50**, **52**. Also shown in FIG. **4** are widths **352** and **354**, legs **356** and **358**, planar surfaces **360**, **362**, **364**, **366**, **368**, **372**, and **374**.

FIG. **4** further has advantages in that one winding **50** winds around one side of core **55**, while winding **52** winds around another side of core **55**, as shown. Such a configuration thus provides for input on one side of inductor **54** and output on the other side with convenient mating to a board layout of PCB **57**.

FIG. **5** shows a two-phase coupled inductor **60**, in accord with one embodiment. Inductor **60** may, for example, serve as inductor **28** of FIG. **1**. The inductor **60** may be formed from first and second magnetic cores **61** and **62**, respectively. The illustration of the cores **61** and **62** is exaggerated for the purpose of showing detail of inductor **60**. The two cores **61** and **62** may be “sandwiched” about the windings **64** and **63**. The dimensions E, C and A, in this embodiment, are part of the calculation that determines a leakage inductance for inductor **60**. The dimensions of D, C, and A, combined with the thickness of the first and second cores **61** and **62**, are part of the calculation that determines a magnetizing inductance of the inductor **60**. For example, assuming dimension D is much greater than E, the equations for leakage inductance and magnetizing inductance can be approximated as:

$$L_1 = \frac{\mu_0 * E * C}{2 * A} \text{ and } \tag{1}$$

$$Lm=\mu_0{}^*D^*C/(4^*A) \tag{2}$$

where μ_0 is the permeability of free space, L_1 is leakage inductance, and L_m is magnetizing inductance. One advantage of this embodiment is apparent in the ability to vary the leakage and the magnetizing inductances by varying the dimensions of inductor **60**. For example, the leakage inductance and the magnetizing inductance can be controllably varied by varying the dimension E (e.g., the distance between the windings **64** and **63**). In one embodiment, the cores **61** and **62** may be formed as conductive prints, or traces, directly with a PCB, thereby simplifying assembly processes of circuit construction such that windings **63**, **64** are also PCB traces that couple through one or more planes of a multi-plane PCB. In one embodiment, the two-phase inductor **60** may be implemented on a PCB as two parallel thin-film magnetic cores **61** and **62**. In another embodiment, inductor **60** may form planar surfaces **63**P and **64**P of respective windings **63**, **64** to facilitate mounting of inductor **60** onto the PCB. Dimensions E, A between windings **63**, **64** may define a passageway through inductor **60**. At least part of this passageway is free from intervening magnetic structure between windings **63**, **64**; air may for example fill the space of the passageway and between windings **63**, **64**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **63**, **64**, and within the passageway; by way of example, the cross-sectional area of the passageway

may be defined by the plane of dimensions A, C, which is perpendicular to a line parallel to dimension E between windings **63**, **64**.

FIG. **6** shows a scalable, multi-phase coupled inductor **70** that may be formed from a plurality of H-shaped magnetic cores **74**, in accord with one embodiment. Inductor **70** may, for example, serve as inductor **28** of FIG. **1**. The inductor **70** may be formed by coupling "legs" **74**A of each H-shaped core **74** together. Each core **74** has one winding **72**. The windings **72** may be wound through the passageways **71** formed by legs **74**A of each core **74**. The winding of each core **74** may be wound prior to coupling the several cores together such that manufacturing of inductor **70** is simplified. By way of example, cores **74** may be made and used later; if a design requires additional phases, more of the cores **74** may be coupled together "as needed" without having to form additional windings **72**. Each core **74** may be mounted on a PCB, such as PCB **57** of FIG. **4**, and be coupled together to implement a particular design. One advantage to inductor **70** is that a plurality of cores **74** may be coupled together to make a multi-core inductor that is scalable. In one embodiment, H-shaped cores **74** cooperatively form a four-phase coupled inductor. Other embodiments may, for example, scale the number of phases of the inductor **70** by coupling more H-shaped cores **74**. For example, the coupling of another H-shaped core **74** may increase the number of phases of the inductor **70** to five. In one embodiment, the center posts **74**C about which the windings **72** are wound may be thinner (along direction D) than the legs **74**A (along direction D). Thinner center posts **74**C may reduce winding resistance and increase leakage inductance without increasing the footprint size of the coupled inductor **70**. Each of the H-shaped cores **74** has a planar surface **74**P, for example, that aligns with other H-shaped cores in the same plane and facilitates mounting of inductor **70** onto PCB **74**S. At least part of one passageway **71**, at any location along direction D within the one passageway, is free from intervening magnetic structure between windings **72**; for example air may fill the three central passageways **71** of inductor **70** and between windings **72** in those three central passageways **71**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **72**, and within passageway **71**.

FIG. **7** shows a scalable, multi-phase coupled inductor **75** formed from a plurality of U-shaped magnetic cores **78** and an equal number of I-shaped magnetic cores **79** (e.g., bars), in accord with one embodiment. Inductor **75** may, for example, serve as inductor **28** of FIG. **1**. The U-shaped cores **78** coupled with the I-shaped cores **79** may form rectangular-shaped core cells **75**A, **75**B, **75**C, and **75**D, each of which is similar to the cell of FIG. **2**, but for the winding placement. The inductor **75** may be formed by coupling each of the rectangular-shaped core cells **75**A, **75**B, **75**C, and **75**D together. The windings **76** and **77** may be wound through the passageways (labeled "APERTURE") formed by the couplings of cores **78** with cores **79** and about core elements. Similar to FIG. **6**, the windings **76** and **77** of each rectangular-shaped core cell may be made prior to coupling with other rectangular-shaped core cells **75**A, **75**B, **75**C, and **75**D such that manufacturing of inductor **75** is simplified; additional inductors **75**, may thus, be implemented "as needed" in a design. One advantage to inductor **75** is that cells **75**A, **75**B, **75**C, and **75**D—and/or other like cells—may be coupled together to make inductor **75** scalable. In the illustrated embodiment of FIG. **7**, rectangular-shaped cells **75**A, **75**B, **75**C, and **75**D cooperatively form a five-phase coupled inductor. Each of the I-shaped cores **79** has a planar surface **79**P, for example, that aligns

with other I-shaped cores in the same plane and facilitates mounting of inductor **75** onto PCB **79**S. At least part of the Apertures is free from intervening magnetic structure between windings **76**, **77**; air may for example fill the space of these passageways and between windings **76**, **77**. By way of example, each Aperture is shown with a pair of windings **76**, **77** passing therethrough, with only air filling the space between the windings **76**, **77**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **76**, **77**, and within each respective Aperture.

FIG. **8** shows a scalable, multi-phase coupled inductor **80** formed from a plurality of U-shaped magnetic cores **81** (or C-shaped depending on the orientation), in accord with one embodiment. Each magnetic core **81** has two lateral members **81**L and an upright member **81**U, as shown. Inductor **80** may, for example, serve as inductor **28** of FIG. **1**. The inductor **80** may be formed by coupling lateral members **81**L of each U-shaped core **81** (except for the last core **81** in a row) together with the upright member **81**U of a succeeding U-shaped core **81**, as shown. The windings **82** and **83** may be wound through the passageways **84** formed between each pair of cores **81**. Scalability and ease of manufacturing advantages are similar to those previously mentioned. For example, winding **82** and its respective core **81** may be identical to winding **83** and its respective core **81**, forming a pair of like cells. More cells can be added to desired scalability. Each of the U-shaped cores **81** has a planar surface **81**P, for example, that aligns with other U-shaped cores **81** in the same plane and facilitates mounting of inductor **80** onto PCB **81**S. At least part of one passageway **84** is free from intervening magnetic structure between windings **82**, **83**; air may for example fill the space of this passageway **84** and between windings **82**, **83**. By way of example, three passageways **84** are shown each with a pair of windings **82**, **83** passing therethrough, with only air filling the space between the windings **82**, **83**. One winding **82** is at the end of inductor **80** and does not pass through such a passageway **84**; and another winding **83** is at another end of inductor **80** and does not pass through such a passageway **84**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **82**, **83**, and within passageway **84**.

FIG. **9** shows a multi-phase coupled inductor **85** formed from a comb-shaped magnetic core **86** and an I-shaped (e.g., a bar) magnetic core **87**, in accord with one embodiment. Inductor **85** may, for example, serve as inductor **28** of FIG. **1**. The inductor **85** may be formed by coupling a planar surface **86**P of "teeth" **86**A of the comb-shaped core **86** to a planar surface **87**P of the I-shaped core **87** in substantially the same plane. The windings **88** and **89** may be wound through the passageways **86**B formed by adjacent teeth **86**A of comb-shaped core **86** as coupled with I-shaped core **87**. The windings **88** and **89** may be wound about the teeth **86**A of the comb-shaped core **86**. FIG. **9** also shows end passageways **200**, planar surfaces **202**, **204**, **206**, **208**, **210**, **212**, **214**, and **224**, height **216**, depth **218**, and widths **220** and **222**. This embodiment may also be scalable by coupling inductor **85** with other inductor structures shown herein. For example, the U-shaped magnetic cores **81** of FIG. **8** may be coupled to inductor **85** to form a multi-phase inductor, or a N+1 phase inductor. The I-shaped core **87** has a planar surface **87**P, for example, that facilitates mounting of inductor **85** onto PCB **87**S. At least part of one passageway **86**B is free from intervening magnetic structure between windings **88**, **89**; air may for example fill the space of this passageway **86**B and between windings **88**, **89**. By way of example, three passageways **86**B are shown each with a pair of windings **88**, **89**

passing therethrough, with only air filling the space between the windings **88**, **89**. One winding **88** is at the end of inductor **85** and does not pass through such a passageway **86**B; and another winding **89** is at another end of inductor **85** and does not pass through such a passageway **86**B. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **88**, **89**, and within passageway **86**B.

In one embodiment, windings **88**, **89** wind around teeth **86**A of core **86**, rather than around I-shaped core **87** or the non-teeth portion of core **86**.

FIG. **10** shows a scalable, multi-phase coupled inductor **90** that may be formed from a comb-shaped magnetic core **92** and an I-shaped (e.g., a bar) magnetic core **93**, in accord with one embodiment. Inductor **90** may, for example, serve as inductor **28** of FIG. **1**. The inductor **90** may be formed by coupling “teeth” **92**A of the comb-shaped core **92** to the I-shaped core **93**, similar to FIG. **8**. The inductor **90** may be scaled to include more phases by the addition of the one more core cells to form a scalable structure. In one embodiment, H-shaped cores **91** (such as those shown in FIG. **6** as H-shaped magnetic cores **74**), may be coupled to cores **92** and **93**, as shown. The windings **94** and **95** may be wound through the passageways **90**A formed by the teeth **92**A as coupled with I-shaped core **93**. The windings **94** and **95** may be wound about the teeth **92**A of core **92** and the “bars” **91**A of H-shaped cores **91**. Scalability and ease of manufacturing advantages are similar to those previously mentioned. Those skilled in the art should appreciate that other shapes, such as the U-shaped cores and rectangular shaped cores, may be formed similarly to cores **92** and **93**. Each of the I-shaped core **92** and the H-shaped cores **91** has a respective planar surface **92**P and **91**P, for example, that aligns in the same plane and facilitates mounting of inductor **90** onto PCB **90**S. At least part of one passageway **90**A is free from intervening magnetic structure between windings **94**, **95**; air may for example fill the space of this passageway **90**A and between windings **94**, **95**. By way of example, five passageways **90**A are shown each with a pair of windings **94**, **95** passing therethrough, with only air filling the space between the windings **94**, **95**. One winding **94** is at the end of inductor **90** and does not pass through such a passageway **90**A; and another winding **95** is at another end of inductor **90** and does not pass through such a passageway **90**A. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **94**, **95**, and within passageway **90**A.

FIGS. **11-13** show staple magnetic cores **102** that may serve to implement a scalable multi-phase coupled inductor **100**. Inductor **100** may, for example, serve as inductor **28** of FIG. **1**. The staple magnetic cores **102** are, for example, U-shaped and may function similar to a “staple”. The staple magnetic cores **102** may connect, or staple, through PCB **101** to bus bars **103** to form a plurality of magnetic core cells. For example, the two bus bars **103** may be affixed to one side of PCB **101** such that the staple magnetic cores **102** traverse through the PCB **101** from the opposite side of the PCB (e.g., via apertures **101**H) to physically couple to the bus bars **103**. One staple magnetic core may implement a single phase for the inductor **100**; thus the inductor **100** may be scalable by adding more of staple magnetic cores **102** and windings **104**, **105**. For example, a two-phase coupled inductor would have two staple magnetic cores **102** coupled to bus bars **103** with each core having a winding, such as windings **104**, **105**; the number of phases are thus equal to the number of staple magnetic cores **102** and windings **104**, **105**. By way of example, inductor **100**, FIG. **11**, shows a 3-phase inductor.

Bus bars **103** may have center axes **402** and staple magnetic cores **102** may have center axes **404**.

Advantages of this embodiment provide a PCB structure that may be designed in layout. As such, PCB real estate determinations may be made with fewer restrictions, as the inductor **100** becomes part of the PCB design. Other advantages of the embodiment are apparent in FIG. **13**. There, it can be seen that the staples **102** may connect to PCB **101** at angles to each PCB trace (i.e., windings **104** and **105**) so as to not incur added resistance while at the same time improving adjustability of leakage inductance. For example, extreme angles, such as 90 degrees, may increase the overall length of a PCB trace, which in turn increases resistance due to greater current travel. Further advantages of this embodiment include the reduction or avoidance of solder joints, which can significantly diminish high current. Additionally, the embodiment may incur fewer or no additional winding costs as the windings are part of the PCB; this may improve dimensional control so as to provide consistent characteristics such as AC resistance and leakage inductance.

Similar to coupled inductor **100**, FIG. **14** shows bar magnetic cores **152**, **153** that serve to implement a scalable coupled inductor **150**. Inductor **150** may, for example, serve as inductor **28** of FIG. **1**. The bar magnetic cores **152**, **153** are, for example, respectively mounted to opposing sides **156**, **157** of PCB **151**. Each of the bar magnetic cores **152**, **153** has, for example, a respective planar surface **152**P, **153**P that facilitates mounting of the bar magnetic cores to PCB **151**. The bar magnetic cores **152**, **153**, in this embodiment, do not physically connect to each other but rather affix to the sides of **156**, **157** such that coupling of the inductor **150** is weaker. The coupling of the inductor **150** may, thus, be determinant upon the thickness of the PCB **151**; this thickness forms a gap between cores **152** and **153**. One example of a PCB that would be useful in such an implementation is a thin polyimide PCB. One bar magnetic core **152** or **153** may implement a single phase for the inductor **150**; and inductor **150** may be scalable by adding additional bar magnetic cores **152** or **153**. For example, a two-phase coupled inductor has two bar magnetic cores **152** coupled to two bus bars **153**, each core having a winding **154** or **155** respectively. The number of phases are therefore equal to the number of bar magnetic cores **152**, **153** and windings **154**, **155**. One advantage of the embodiment of FIG. **14** is that no through-holes are required in PCB **151**. The gap between cores **152** and **153** slightly reduces coupling so as to make the DC-to-DC converter system using coupled inductor **150** more tolerant to DC current mismatch. Another advantage is that all the cores **152**, **153** are simple, inexpensive I-shaped magnetic bars. Cores **152** may have center axes **408**, and cores **153** may have center axes **406**.

FIGS. **15-16** each show a multi-phase coupled inductor (e.g., **110** and **120**, respectively) with through-board integration, in accord with other embodiments. FIG. **15** shows a coupled inductor **110** that may be formed from a comb-shaped core **111** coupled to an I-shaped core **112** (e.g., a bar), similar to that shown in FIG. **9**. In this embodiment, the cores **111** and **112** may be coupled through PCB **113** and are integrated with PCB **113**. The windings **114**, **115** may be formed in PCB **113** and/or as printed circuit traces on PCB **113**, or as wires connected thereto.

In FIG. **15**, comb-shaped core **111** and I-shaped core **112** form a series of passageways **117** within coupled inductor **110**. At least part of one passageway **117** is free from intervening structure between windings **114**, **115**; air may for example fill the space of this passageway **117** and between windings **114**, **115**. By way of example, three passageways **117** are shown each with a pair of windings **114**, **115** passing

therethrough, with non-magnetic structure of PCB **113** filling some or all of the space between the windings **114**, **115**. One winding **114** is at the end of inductor **110** and does not pass through such a passageway **117**; and another winding **115** is at another end of inductor **110** and does not pass through such a passageway **117**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **114**, **115**, and within passageway **117**.

FIG. **16** shows another through-board integration in a coupled inductor **120**. In this embodiment, magnetic cores **121** and **122** may be coupled together by "sandwiching" the cores **121**, **122** about PCB **123**. The connections to the cores **121**, **122** may be implemented via holes **126** in the PCB **123**. The holes **126** may be filled with a ferromagnetic powder and/or bar that couples the two cores together, when sandwiched with the PCB **123**. Similarly, the windings **124**, **125** may be formed in PCB **123** and/or as printed circuit traces on PCB **123**, or as wires connected thereto. Inductors **110** and **120** may, for example, serve as inductor **28** of FIG. **1**. In this embodiment, the windings **114** and **115** are illustrated as PCB traces located within a center, or interior, plane of the PCB **123**. Those skilled in the art should readily appreciate that the windings **114** and **115** may be embedded into any layer of the PCB and/or in multiple layers of the PCB, such as exterior and/or interior layers of the PCB.

In FIG. **16**, cores **121** and **122** and ferromagnetic-filled holes **126** form a series of passageways **118** within coupled inductor **120**. At least part of one passageway **118** is free from intervening structure between windings **124**, **125**; air may for example fill the space of this passageway **118** and between windings **124**, **125**. By way of example, three passageways **118** are shown each with a pair of windings **124**, **125** passing therethrough, with non-magnetic structure of PCB **123** filling some or all of the space between the windings **124**, **125**. One winding **124** is at the end of inductor **120** and does not pass through such a passageway **118**; and another winding **125** is at another end of inductor **120** and does not pass through such a passageway **118**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **124**, **125**, and within passageway **118**.

FIG. **17** shows a multi-phase scalable coupled ring-core inductor **130**, in accord with one embodiment. The inductor **130** may be formed from multiple ring magnetic cores **131**A, **131**B, and **131**C. In this embodiment, cores **131**A, **131**B, and **131**C may be coupled to one another. The ring magnetic cores **131**A, **131**B, and **131**C may have respective planar surfaces **131**AP, **131**BP, and **131**CP, for example, that align in the same plane, to facilitate mounting with electronics such as a PCB. Each core may have an passageway **135** through which windings **132**, **133**, and **134** may be wound. As one example, cores **131**A and **131**B may be coupled to one another as winding **133** may be wound through the passageways and about the cores. Similarly, cores **131**B and **131**C may be coupled to one another as winding **132** may be wound through the passageways **135** of those two cores. Cores **131**C and **131**A may be coupled to one another as winding **134** is wound through the passageways of those two cores. In another embodiment, the multiple ring magnetic cores **131**A, **131**B, and **131**C may be coupled together by windings such that inductor **130** appears as a string or a chain. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between the windings within each respective passageway **135**.

While some inductor embodiments include two-phase coupling, such as those shown in FIGS. **2-5**, it is not intended that inductor coupling should be limited to two-phases. For example, a coupled inductor with two windings would function as a two-phase coupled inductor with good coupling, but coupling additional inductors together may advantageously increase the number of phases as a matter of design choice. Integration of multiple inductors that results in increased phases may achieve current ripple reduction of a power unit coupled thereto; examples of such are shown in FIGS. **6-8**, **10**, and **17**. Coupling two or more two-phase inductor structures together to create a scalable N-phase coupled inductor may achieve an increased number of phases of an inductor. The windings of such an N-phase coupled inductor may be wound through the passageways and about the core such as those shown in FIGS. **6-8**, **10**, and **17**.

Since certain changes may be made in the above methods and systems without departing from the scope hereof, one intention is that all matter contained in the above description or shown in the accompanying drawings be interpreted as illustrative and not in a limiting sense. By way of example, those skilled in the art should appreciate that items as shown in the embodiments may be constructed, connected, arranged, and/or combined in other formats without departing from the scope of the invention. Another intention includes an understanding that the following claims are to cover all generic and specific features of the invention described herein, and all statements of the scope of the invention which, as a matter of language, might be said to fall there between.

We claim:

1. An N-phase coupled inductor for magnetically coupling N phases of a power converter, comprising:

a magnetic core including a first and a second magnetic element and N connecting magnetic elements, N being an integer greater than one, the first and second magnetic elements being disposed parallel to each other and separated by a linear separation distance, each connecting magnetic element being coupled to the first and second magnetic elements; and

N windings, each of the N windings for electrically connecting to a respective phase of the power converter,

each connecting magnetic element having a respective one of the N windings wound at least partially thereabout,

two of the N windings being at least partially wound about a respective one of the N connecting magnetic elements and one of the first and second magnetic elements, and

N−2 of the N windings being at least partially wound about a respective one of the N connecting magnetic elements and both of the first and second magnetic elements.

2. The coupled inductor of claim **1**, each of the first and second magnetic elements having an I-shape.

3. The coupled inductor of claim **1**, each of the connecting magnetic elements having a U-shape.

4. The coupled inductor of claim **1**, each of the connecting magnetic elements having an I-shape.

5. The coupled inductor of claim **1**, each connecting magnetic element being disposed such that a center axis of the connecting magnetic element is about orthogonal to a center axis of the first and second magnetic elements.

6. The coupled inductor of claim **1**, each connecting magnetic element being disposed such that a center axis of the connecting magnetic element forms a first angle with respect to a center axis of the first magnetic element and a second angle with respect a center axis of the second magnetic element, the first and second angles being less than ninety degrees.

7. The coupled inductor of claim **1**, each winding having rectangular cross section.

8. An N-phase coupled inductor for magnetically coupling N phases of a power converter, comprising:

a printed circuit board for supporting the coupled inductor, the printed circuit board having a first side opposite a second side, the printed circuit board forming 2N apertures, N being an integer greater than one;

a magnetic core including a first and a second magnetic element and N connecting magnetic elements, the first and second magnetic elements being disposed parallel to each other on the first side of the printed circuit board, the first and second magnetic elements being separated by a linear separation distance along the first side of the printed circuit board, each connecting magnetic element being disposed on the second side of the printed circuit board and coupled to the first and second magnetic elements via two of the 2N apertures of the printed circuit board; and

N windings formed on the printed circuit board, each of the N windings for electrically connecting to a respective phase of the power converter,

each connecting magnetic element having a respective one the N windings wound at least partially thereabout,

two of the N windings being at least partially wound about a respective one of the N connecting magnetic elements and one of the first and second magnetic elements, and

N−2 of the N windings being at least partially wound about a respective one of the N connecting magnetic elements and both of the first and second magnetic elements.

9. The coupled inductor of claim **8**, each of the first and second magnetic elements having an I-shape.

10. The coupled inductor of claim **8**, each of the connecting magnetic elements having a U-shape.

11. The coupled inductor of claim **8**, each connecting magnetic element being disposed such that a center axis of the connecting magnetic element is about orthogonal to a center axis of the first and second magnetic elements.

12. The coupled inductor of claim **8**, each connecting magnetic element being disposed such that a center axis of the connecting magnetic element forms a first angle with respect to a center axis of the first magnetic element and a second angle with respect a center axis of the second magnetic element, the first and second angles being less than ninety degrees.

13. The coupled inductor of claim **8**, each winding forming an angle in a plane of the printed circuit board, the angle being less than ninety degrees.

14. An N-phase coupled inductor for magnetically coupling N phases of a power converter, comprising:

a magnetic core including a first and a second magnetic element and N connecting magnetic elements, N being an integer greater than one, the first and second magnetic elements being disposed parallel to each other and separated by a linear separation distance, each connecting magnetic element being coupled to the first and second magnetic elements, the first and second magnetic elements and the N connecting elements cooperatively forming N−1 passageways; and

N windings, each of the N windings for electrically connecting to a respective phase of the power converter,

each winding being wound about a respective connecting element and at least partially through at least one passageway, and

each passageway having two of the N windings wound at least partially therethrough.

15. The coupled inductor of claim **14**, each of the first and second magnetic elements having an I-shape.

16. The coupled inductor of claim **14**, each of the connecting magnetic elements having a U-shape.

17. The coupled inductor of claim **14**, each of the connecting magnetic elements having an I-shape.

18. The coupled inductor of claim **14**, each connecting magnetic element being disposed such that a center axis of the connecting magnetic element is about orthogonal to a center axis of the first and second magnetic elements.

19. The coupled inductor of claim **14**, each connecting magnetic element being disposed such that a center axis of the connecting magnetic element forms a first angle with respect to a center axis of the first magnetic element and a second angle with respect a center axis of the second magnetic element, the first and second angles being less than ninety degrees.

20. The coupled inductor of claim **14**, each winding having rectangular cross section.

* * * * *

EXHIBIT 10

US007772955B1

(12) **United States Patent**
Li et al.

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(45) **Date of Patent: Aug. 10, 2010**

(54) **METHOD FOR MAKING MAGNETIC COMPONENTS WITH N-PHASE COUPLING, AND RELATED INDUCTOR STRUCTURES**

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H01F 5/00 (2006.01)

(52) **U.S. Cl.** **336/200**

(58) **Field of Classification Search** 336/65, 336/83, 192, 200, 220–223, 232; 257/531
See application file for complete search history.

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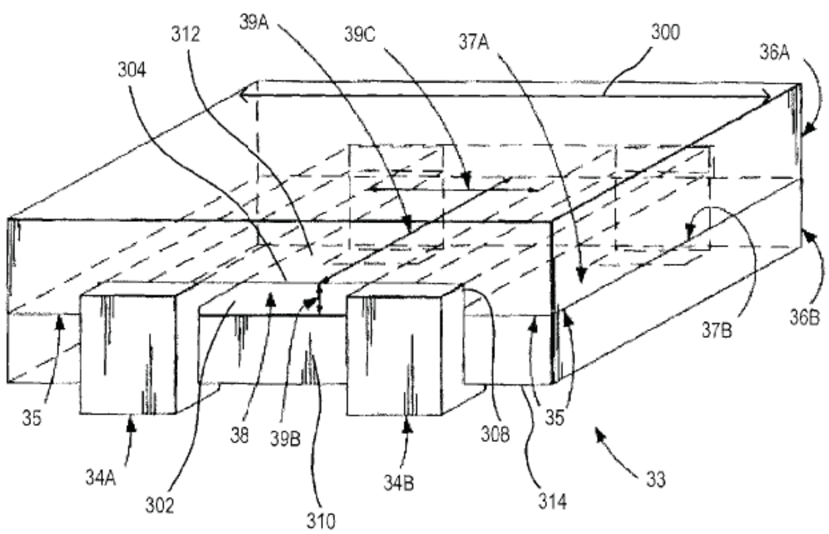
(57) **ABSTRACT**

Methods and structures for constructing a magnetic core of a coupled inductor. The method provides for constructing N-phase coupled inductors as both single and scalable magnetic structures, where N is an integer greater than 1. The method additionally describes how such a construction of the magnetic core may enhance the benefits of using the scalable N-phase coupled inductor. The first and second magnetic cores may be formed into shapes that, when coupled together, may form a single scalable magnetic core. For example, the cores can be fashioned into shapes such as a U, an I, an H, a ring, a rectangle, and a comb, that cooperatively form the single magnetic core.

29 Claims, 13 Drawing Sheets



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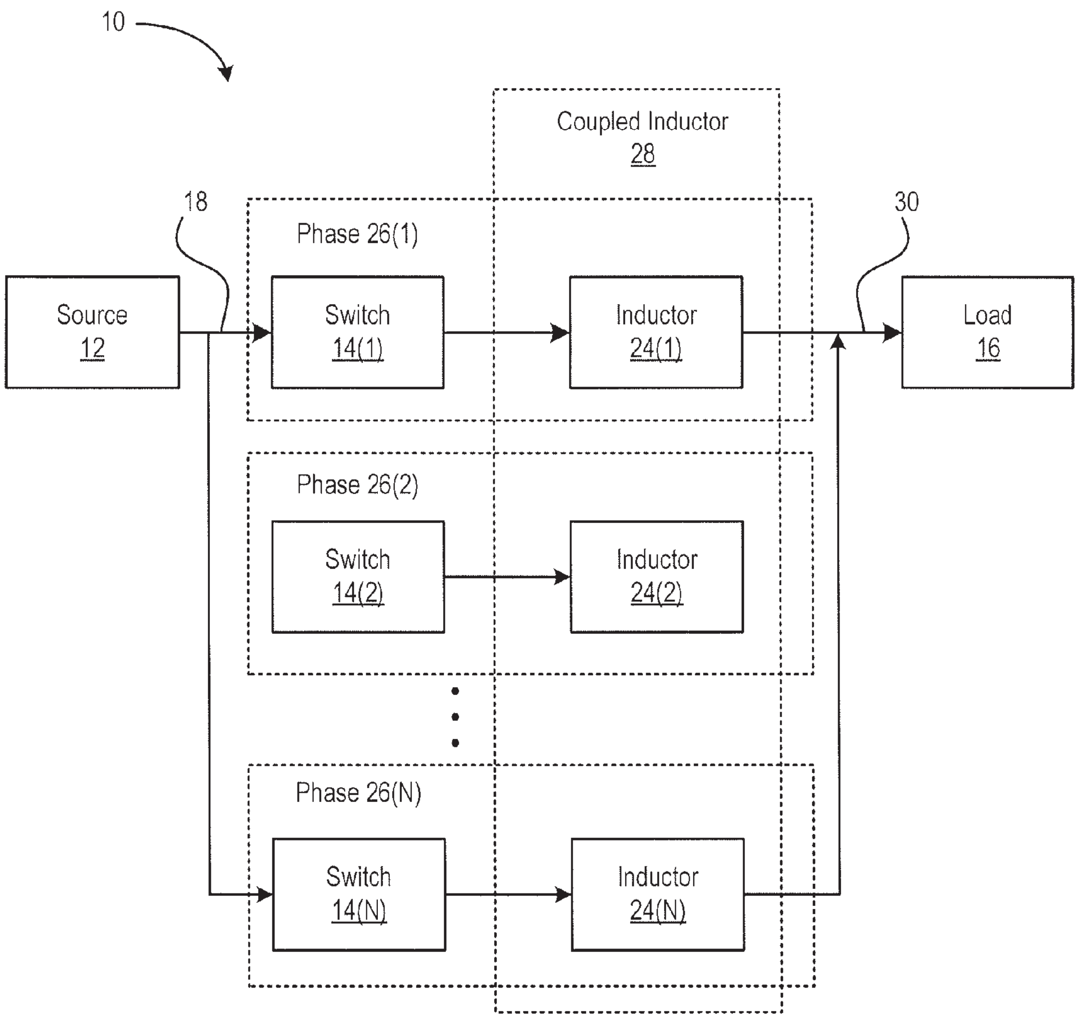
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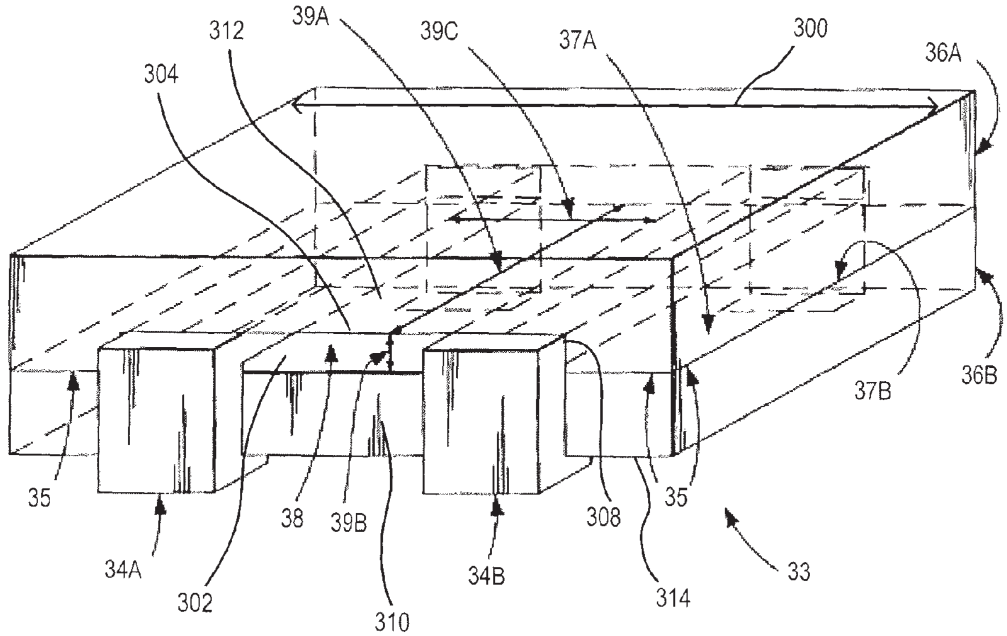
Coupled Inductor
28
18
30
Phase 26(1)
Source
12
Switch
14(1)
Inductor
24(1)
Load
16
Phase 26(2)
Switch
14(2)
Inductor
24(2)
Phase 26(N)
Switch
14(N)
Inductor
24(N)

FIG. 1



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39A
39C
37A
300
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36B
37B
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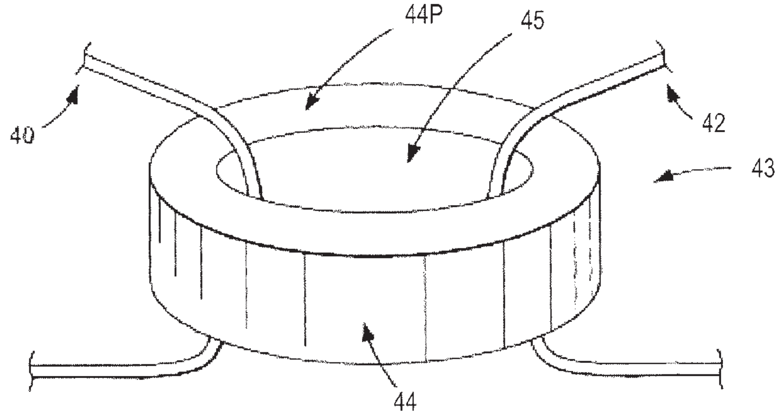
38
39B
308
35
34A
302
310
34B
314
33

FIG. 2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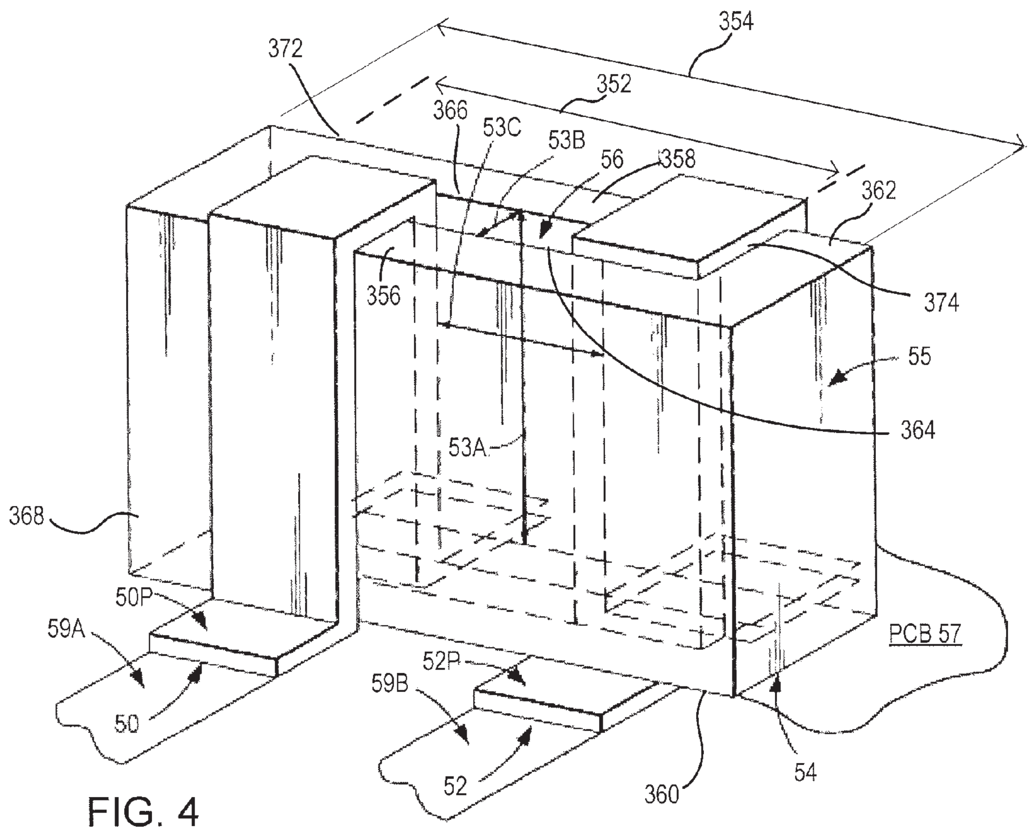
40
42
43
44

FIG. 3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372
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53C
53B
56
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364
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59A
52P
59B
50
52
360
54
PCB 57

FIG. 4

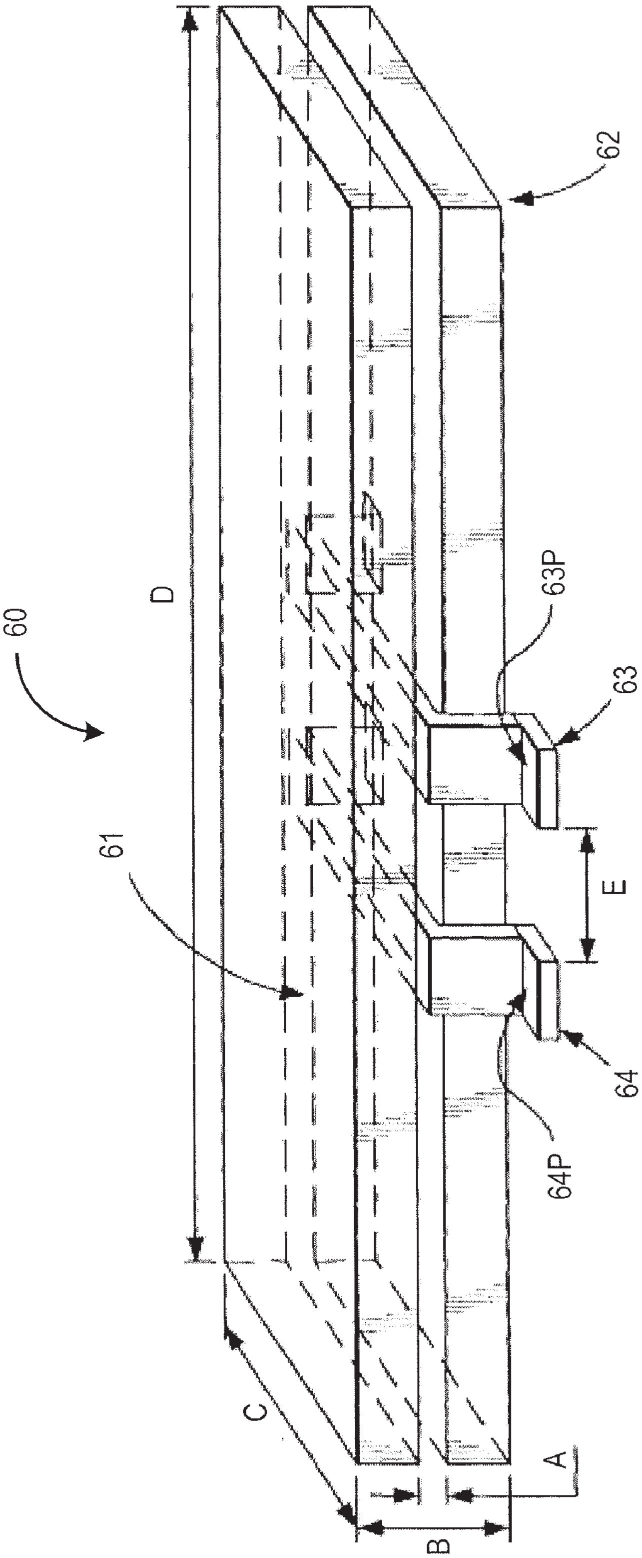
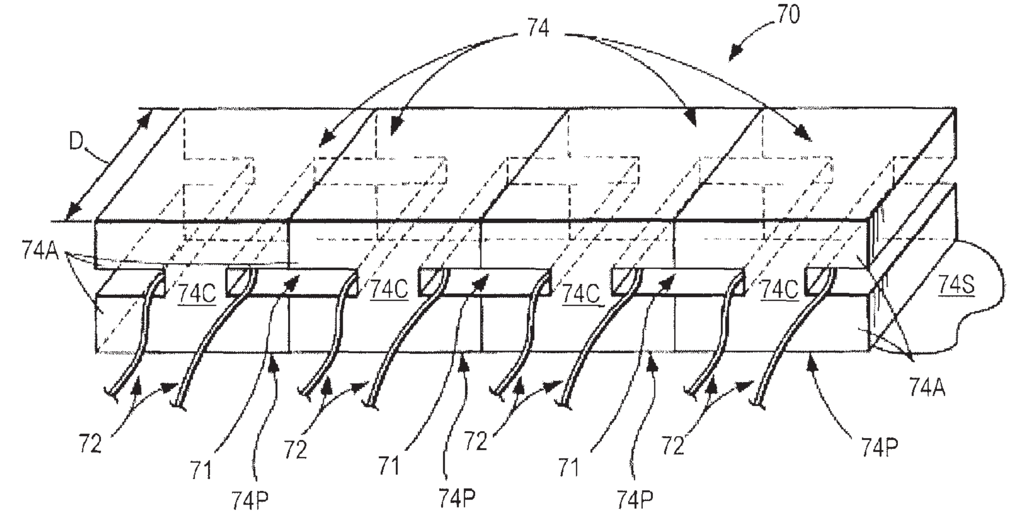
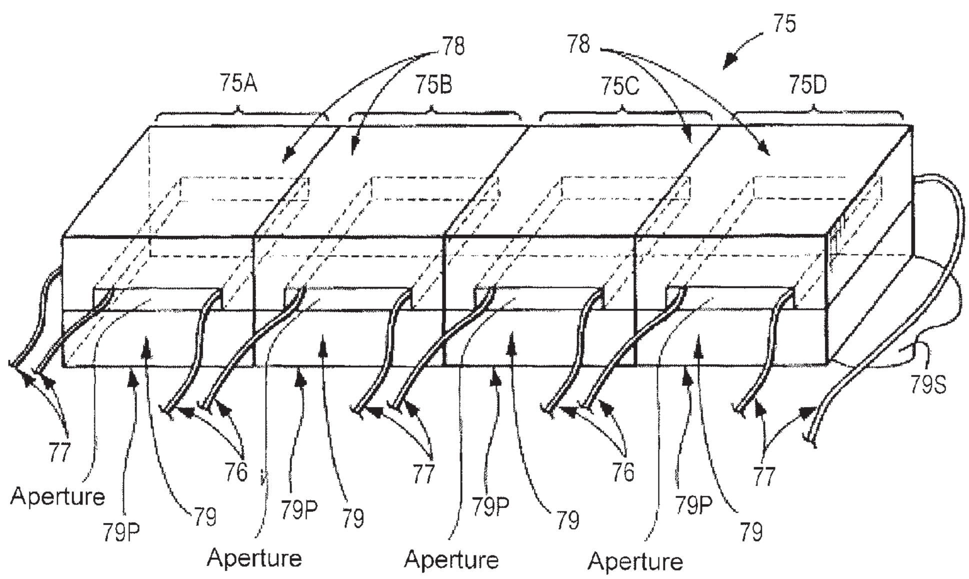


FIG. 5



74
70
D
74A
74C
74C
74C
74C
74S
74A
72
71
74P
72
71
74P
72
71
74P
72
74P

FIG. 6



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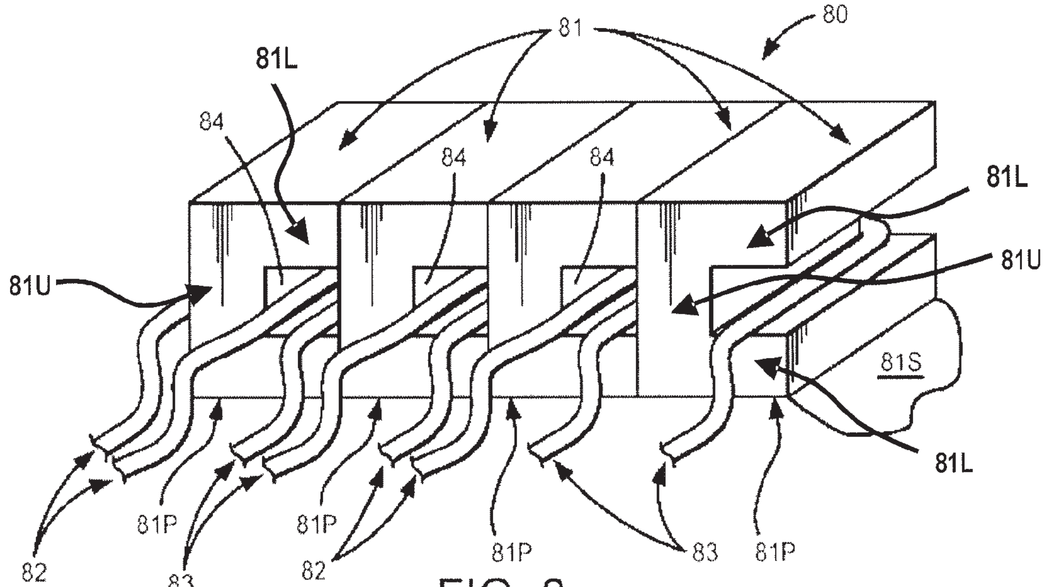
78
78
75A
75B
75C
75D
79S
77
Aperture
79P
76
79
79P
79
Aperture
77
79P
79
Aperture
76
79P
Aperture
77
79

FIG. 7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84
84
84
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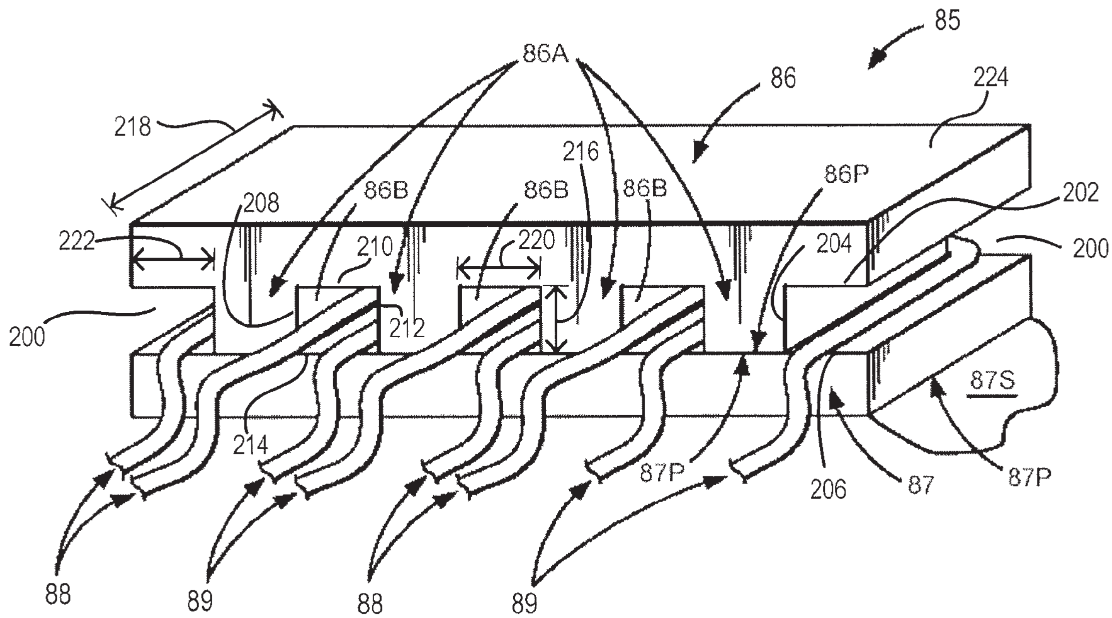
81U
81U
81S
81L
81P
81P
81P
81P
82
83
82
83

FIG. 8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86B
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87P
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87P
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88
89

FIG. 9

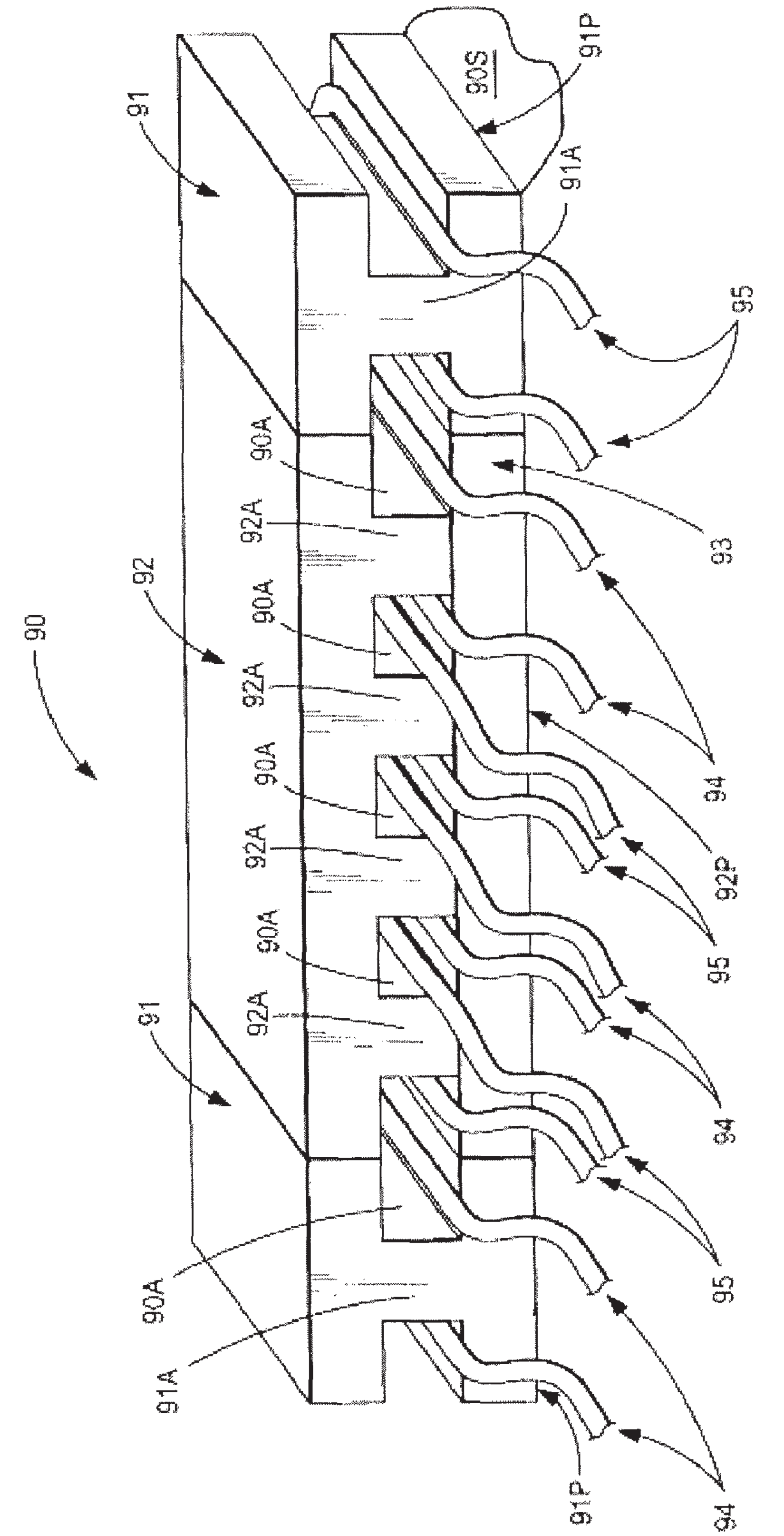


FIG. 10

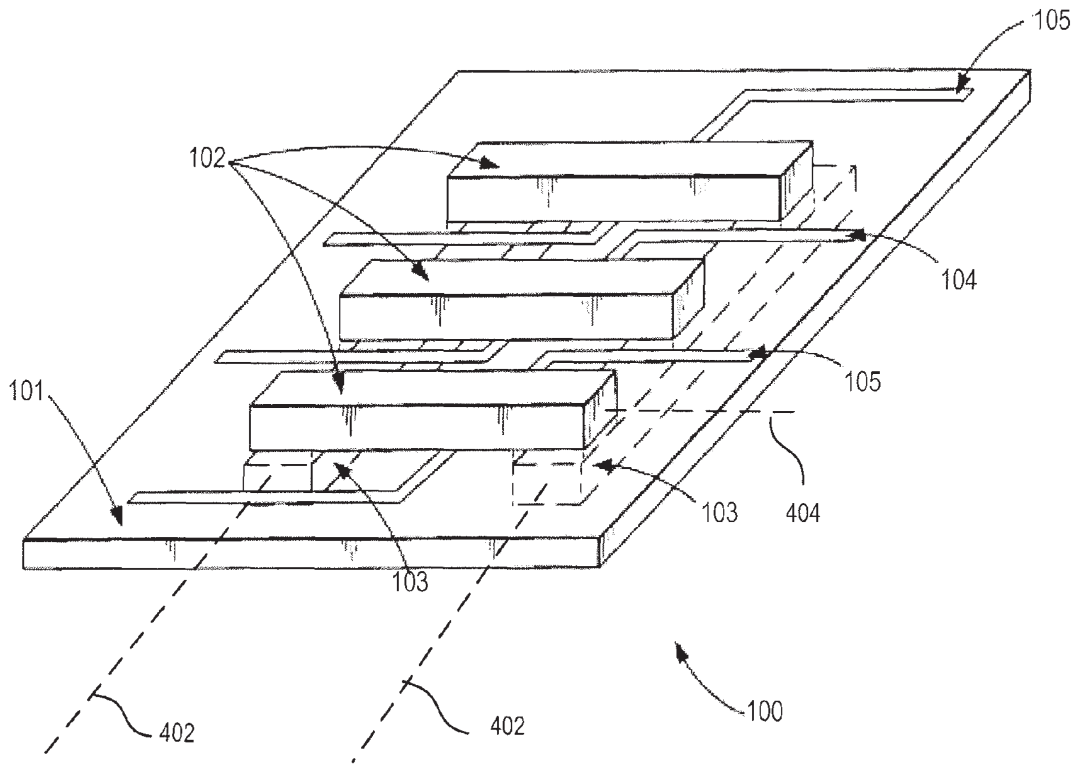


FIG. 11

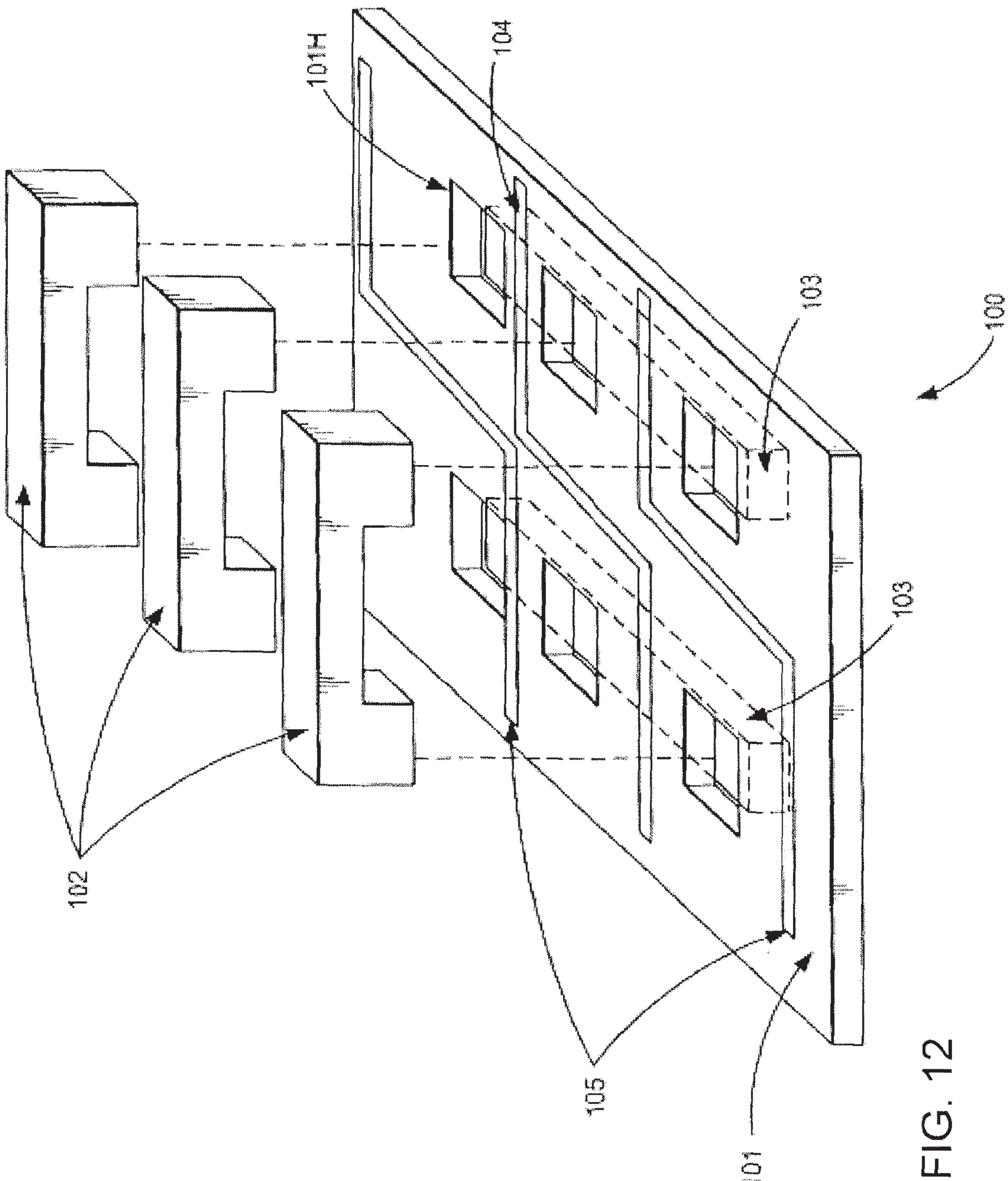


FIG. 12

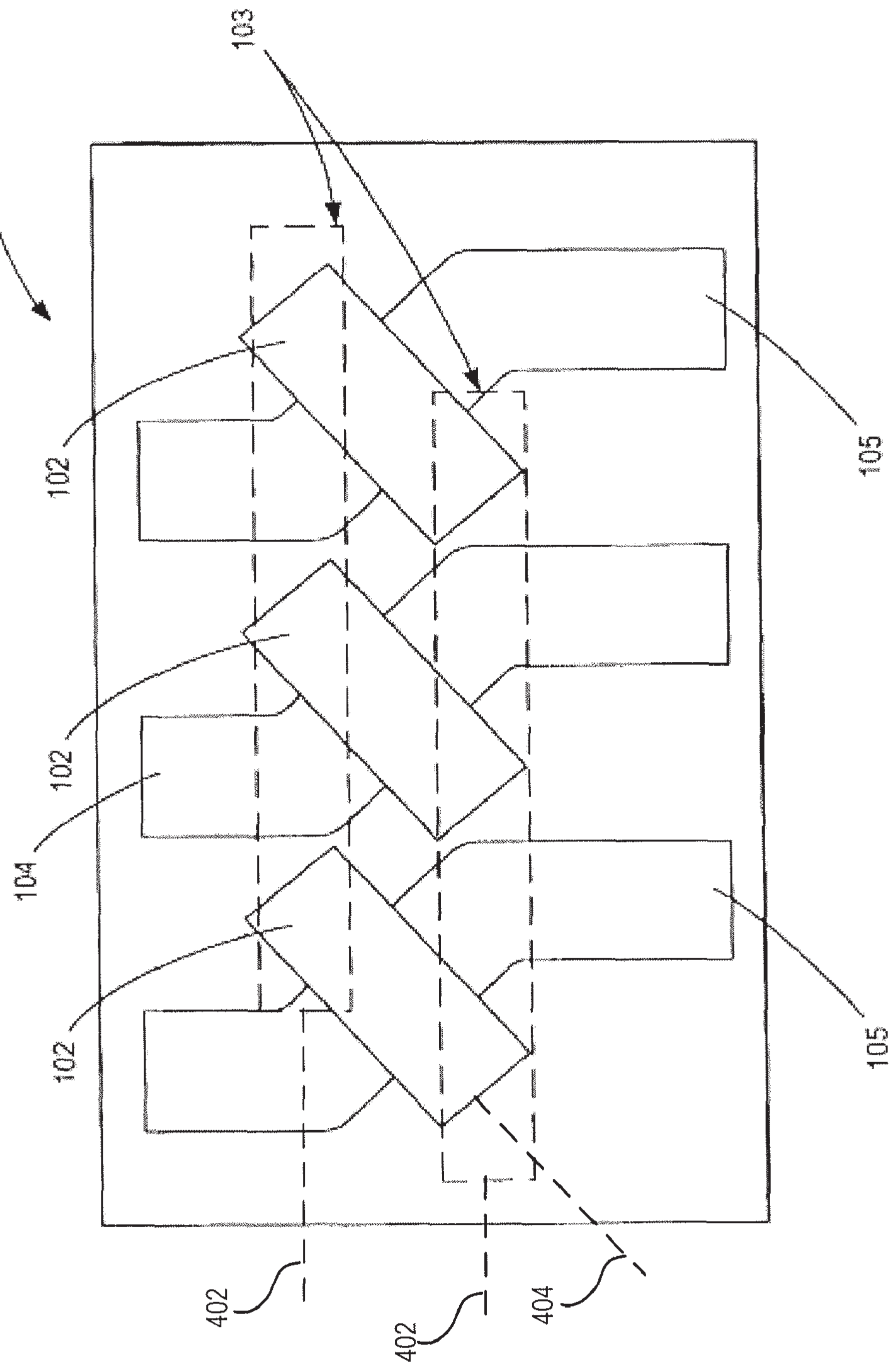
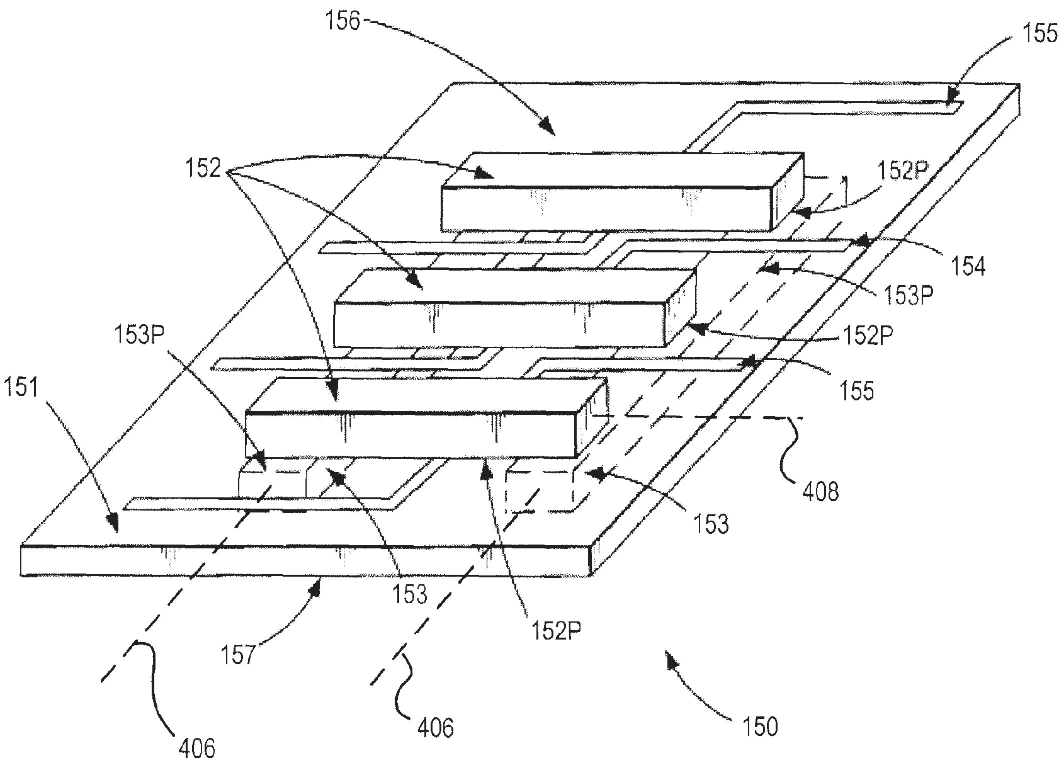


FIG. 13



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155
152
152P
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153P
152P
153P
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408
153
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157
152P
406
406
150

FIG. 14

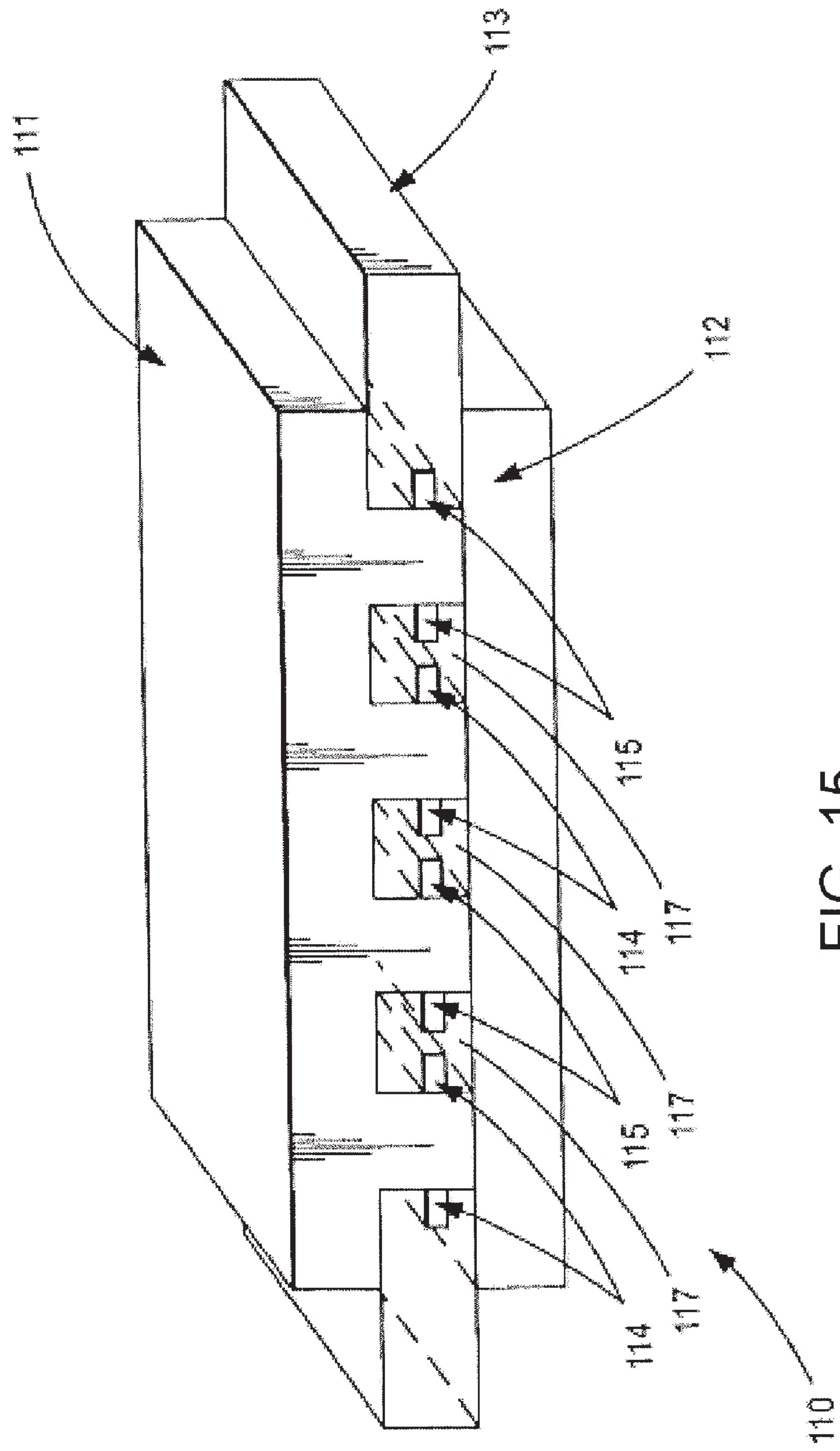

FIG. 15

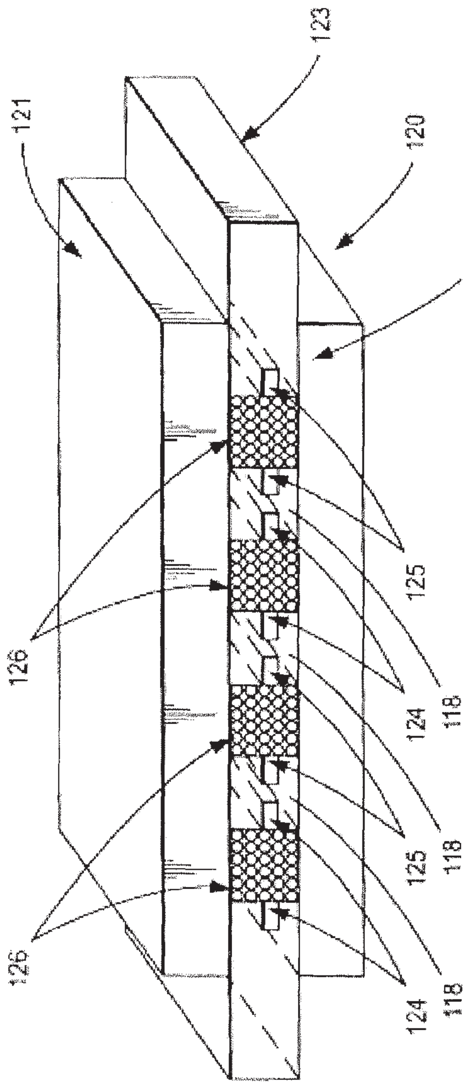
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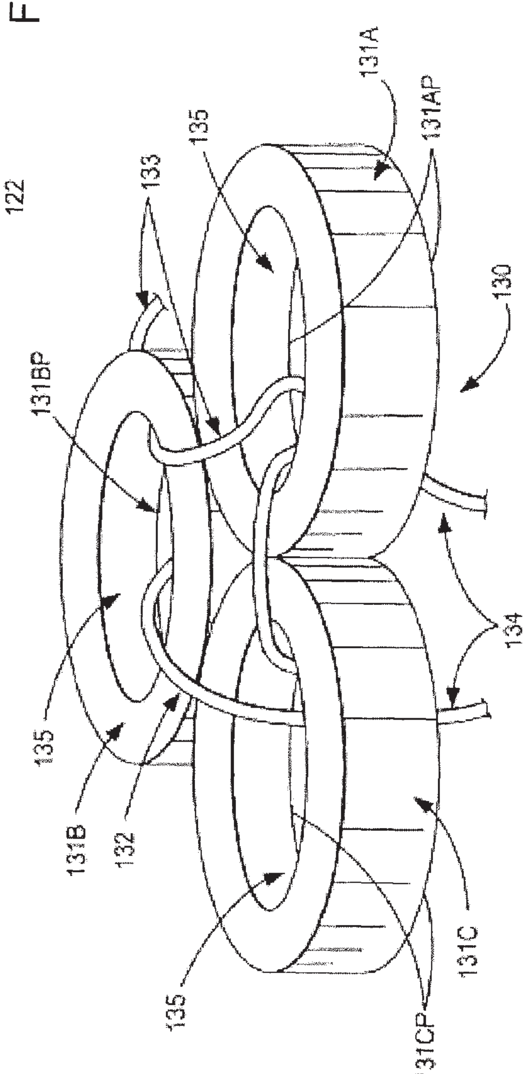
FIG. 16


131A
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131BP
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135
131B
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135
131C
131CP

FIG. 17

METHOD FOR MAKING MAGNETIC COMPONENTS WITH N-PHASE COUPLING, AND RELATED INDUCTOR STRUCTURES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a divisional of U.S. patent application Ser. No. 10/318,896, filed 13 Dec. 2002, which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates generally to making DC-to-DC converters. More specifically the invention relates to construction of a coupled inductor within a multi-phase DC-to-DC converter.

2. Background of the Invention

A DC-to-DC converter, as known in the art, provides an output voltage that is a step-up, a step-down, or a polarity reversal of the input voltage source. Certain known DC-to-DC converters have parallel power units with inputs coupled to a common DC voltage source and outputs coupled to a load, such as a microprocessor. Multiple power-units can sometimes reduce cost by lowering the power and size rating of components. A further benefit is that multiple power units provide smaller per-power-unit peak current levels, combined with smaller passive components.

The prior art also includes switching techniques in parallel-power-unit DC-to-DC converters. By way of example, power units may be switched with pulse width modulation (PWM) or with pulse frequency modulation (PFM). Typically, in a parallel-unit buck converter, the energizing and de-energizing of the inductance in each power unit occurs out of phase with switches coupled to the input, inductor and ground. Additional performance benefits are provided when the switches of one power unit, coupling the inductors to the DC input voltage or to ground, are out of phase with respect to the switches in another power unit. Such a "multi-phase," parallel power unit technique results in ripple current cancellation at a capacitor, to which all the inductors are coupled at their respective output terminals.

It is clear that smaller inductances are needed in DC-to-DC converters to support the response time required in load transients and without prohibitively costly output capacitance. More particularly, the capacitance requirements for systems with fast loads, and large inductors, may make it impossible to provide adequate capacitance configurations, in part due to the parasitic inductance generated by a large physical layout. But smaller inductors create other issues, such as the higher frequencies used in bounding the AC peak-to-peak current ripple within each power unit. Higher frequencies and smaller inductances enable shrinking of part size and weight. However, higher switching frequencies result in more heat dissipation and lower efficiency. In short, small inductance is good for transient response, but large inductance is good for AC current ripple reduction and efficiency.

The prior art has sought to reduce the current ripple in multiphase switching topologies by coupling inductors. For example, one system set forth in U.S. Pat. No. 5,204,809, incorporated herein by reference, couples two inductors in a dual-phase system driven by an H bridge to help reduce ripple current. In one article, *Investigating Coupling Inductors in the Interleaving QSW VRM, IEEE APEC* (Wong, February 2000), slight benefit is shown in ripple reduction by coupling two windings using presently available magnetic core shapes.

However, the benefit from this method is limited in that it only offers slight reduction in ripple at some duty cycles for limited amounts of coupling.

One known DC-to-DC converter offers improved ripple reduction that either reduces or eliminates the afore-mentioned difficulties. Such a DC-to-DC converter is described in commonly owned U.S. Pat. No. 6,362,986 issued to Schultz et al., incorporated herein by reference. The '986 patent can improve converter efficiency and reduce the cost of manufacturing DC-to-DC converters.

Specifically, the '986 patent shows one system that reduces the ripple of the inductor current in a two-phase coupled inductor within a DC-to-DC buck converter. The '986 patent also provides a multi-phase transformer model to illustrate the working principles of multi-phase coupled inductors. It is a continuing problem to address scalability and implementation issues DC-to-DC converters.

As circuit components and, thus, printed circuit boards (PCB), become smaller due to technology advancements, smaller and more scalable DC-to-DC converters are needed to provide for a variety of voltage conversion needs. One specific feature presented hereinafter is to provide a DC-to-DC converter, the DC-to-DC converter being scalable in some embodiments. Another feature is to provide a converter that is mountable to a PCB. Yet another feature is to provide a lower cost manufacturing methodology for DC-to-DC converters, as compared to the prior art. These and other features will be apparent in the description that follows.

SUMMARY OF THE INVENTION

As used herein, a "coupled" inductor implies an interaction between multiple inductors of different phases. Coupled inductors described herein may be used within DC-to-DC converters or within a power converter for power conversion applications, for example.

A method of one aspect provides for constructing a magnetic core. Such a core is, for example, useful in applications detailed in the '986 patent. In one aspect, the method provides for constructing N-phase coupled inductors as both single and scalable magnetic structures, where N is greater than 1. An N-phase inductor as described herein may include N-number of windings. One method additionally describes construction of a magnetic core that enhances the benefits of using the scalable N-phase coupled inductor.

In one aspect, the N-phase coupled inductor is formed by coupling first and second magnetic cores in such a way that a planar surface of the first core is substantially aligned with a planar surface of the second core in a common plane. The first and second magnetic cores may be formed into shapes that, when coupled together, may form a single scalable magnetic core having desirable characteristics, such as ripple current reduction and ease of implementation. In one example, the cores are fashioned into shapes, such as a U-shape, an I-shape (e.g., a bar), an H-shape, a ring-shape, a rectangular-shape, or a comb. In another example, the cores could be fashioned into a printed circuit trace within a PCB.

In another aspect, certain cores form passageways through which conductive windings are wound when coupled together. Other cores may already form these passageways (e.g., the ring-shaped core and the rectangularly shaped core). For example, two H-shaped magnetic cores may be coupled at the legs of each magnetic core to form a passageway. As another example, a multi-leg core may be formed as a comb-shaped core coupled to an I-shaped core. In yet another example, two I-shaped cores are layered about a PCB such that passageways are formed when the two cores are coupled

to one another at two or more places, or when pre-configured holes in the PCB are filled with a ferromagnetic powder.

Advantages of the method and structures herein include a scalable and cost effective DC-to-DC converter that reduces or nearly eliminates ripple current. The methods and structures further techniques that achieve the benefit of various performance characteristics with a single, scalable, topology.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows one multi-phase DC-to-DC converter system;

FIG. **2** shows one two-phase coupled inductor;

FIG. **3** shows one two-phase coupled ring-core inductor;

FIG. **4** shows one vertically mounted two-phase coupled inductor;

FIG. **5** shows one plate structured two-phase coupled inductor;

FIG. **6** shows one scalable multi-phase coupled inductor with H-shaped cores;

FIG. **7** shows one scalable multi-phase coupled inductor with rectangular-shaped cores;

FIG. **8** shows one scalable multi-phase coupled inductor with U-shaped cores;

FIG. **9** shows one integrated multi-phase coupled inductor with a comb-shaped core;

FIG. **10** shows one scalable multi-phase coupled inductor with combinations of shaped cores;

FIG. **11** shows one scalable multi-phase coupled inductor with "staple" cores;

FIG. **12** shows an assembly view of the coupled inductor of FIG. **11**;

FIG. **13** shows a surface view of the inductor of FIG. **11**;

FIG. **14** shows one scaleable coupled inductor with bar magnet cores;

FIG. **15** shows one multi-phase coupled inductor with through-board integration;

FIG. **16** shows another multi-phase coupled inductor with through-board integration; and

FIG. **17** shows one scalable multi-phase coupled ring-core inductor.

DETAILED DESCRIPTION OF THE DRAWINGS

FIG. **1** shows a multi-phase DC-to-DC converter system **10**. System **10** includes a power source **12** electrically coupled with N switches **14** and N inductors **24**, with N=2, for supplying power to a load **16**. Each switch and inductor pair **14**, **24** represent one phase **26** of system **10**, as shown. Inductors **24** cooperate together as a coupled inductor **28**. Power source **12** may, for example, be either a DC power source, such as a battery, or an AC power source cooperatively coupled to a rectifier, such as a bridge rectifier, to provide DC power in signal **18**. Each switch **14** may include a plurality of switches to perform the functions of DC-to-DC converter system **10**.

In operation, DC-to-DC converter system **10** converts an input signal **18** from source **12** to an output signal **30**. The voltage of signal **30** may be controlled through operation of switches **14**, to be equal to or different from signal **18**. Specifically, coupled inductor **28** has one or more windings (not shown) that extend through and about inductors **24**, as described in detail below. These windings attach to switches **14**, which collectively operate to regulate the output voltage of signal **30** by sequentially switching inductors **24** to signal **18**.

When N=2, system **10** may for example be used as a two-phase power converter, (e.g., power supply). System **10** may also be used in both DC and AC based power supplies to replace a plurality of individual discrete inductors such that coupled inductor **28** reduces inductor ripple current, filter capacitances, and/or PCB footprint sizes, while delivering higher system efficiency and enhanced system reliability. Other functional and operational aspects of DC-to-DC converter system **10** may be exemplarily described in the '986 patent, features of coupled inductor **28** are described in detail below in connection with FIG. **2**-FIG. **17**. Those skilled in the art appreciate that system **10** may be arranged with different topologies to provide a coupled inductor **28** and without departing from the scope hereof.

FIG. **2** shows a two-phase coupled inductor **33**, in accord with one embodiment. Inductor **33** may, for example, serve as inductor **28** of FIG. **1**, with N=2. The two-phase coupled inductor **33** may include a first magnetic core **36**A and a second magnetic core **36**B. The first and second magnetic cores **36**A, **36**B, respectively, are coupled together such that planar surfaces **37**A, **37**B, respectively, of each core are substantially aligned in a common plane, represented by line **35**. When the two magnetic cores **36**A and **36**B are coupled together, they cooperatively form a single magnetic core for use as a two-phase coupled inductor **33**.

In this embodiment, the first magnetic core **36**A may be formed from a ferromagnetic material into a U-shape. The second magnetic core **36**B may be formed from the same ferromagnetic material into a bar, or I-shape, as shown. As the two magnetic cores **36**A, **36**B are coupled together, they form a passageway **38** through which windings **34**A, **34**B are wound. The windings **34**A, **34**B may be formed of a conductive material, such as copper, that wind though and about the passageway **38** and the magnetic core **36**B. Moreover, those skilled in art should appreciate that windings **34**A, **34**B may include a same or differing number of turns about the magnetic core **36**B. Windings **34**A, **34**B are shown as single turn windings, to decrease resistance through inductor **33**.

The windings **34**A and **34**B of inductor **33** may be wound in the same or different orientation from one another. The windings **34**A and **34**B may also be either wound about the single magnetic core in the same number of turns or in a different number of turns. The number of turns and orientation of each winding may be selected so as to support the functionality of the '986 patent, for example. By orienting the windings **34**A and **34**B in the same direction, the coupling is directed so as to reduce the ripple current flowing in windings **34**A, **34**B.

Those skilled in the art should appreciate that a gap (not shown) may exist between magnetic cores **36**A, **36**B, for example to reduce the sensitivity to direct current when inductor **33** is used within a switching power converter. Such a gap is for example illustratively discussed as dimension A, FIG. **5**.

The dimensional distance between windings **34**A, **34**B may also be adjusted to adjust leakage inductance. Such a dimension is illustratively discussed as dimension E, FIG. **5**.

As shown, magnetic core **36**A is a "U-shaped" core while magnetic core **36**B is an unshaped flat plate. Those skilled in the art should also appreciate that coupled inductor **33** may be formed with magnetic cores with different shapes. By way of example, two "L-shaped" or two "U-shaped" cores may be coupled together to provide like overall form as combined cores **36**A, **36**B, to provide like functionality within a switching power converter. Cores **36**A, **36**B may be similarly replaced with a solid magnetic core block with a hole therein to form passageway **38**. At least part of passageway **38** is free

from intervening magnetic structure between windings **34**A, **34**B; air or non-magnetic structure may for example fill the space of passageway **38** and between the windings **34**A, **34**B. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **34**A, **34**B, and within passageway **38**; by way of example, the cross-sectional area of passageway **38** may be defined by the plane of dimensions **39**A (depth), **39**B (height), which is perpendicular to a line **39**C (separation distance) between windings **34**A, **34**B.

FIG. **2** also illustrates one advantageous feature associated with windings **34**A, **34**B. Specifically, each of windings **34**A, **34**B is shown with a rectangular cross-section that, when folded underneath core **36**B, as shown, produces a tab for soldering to a PCB, and without the need for a separate item. Other windings discussed below may have similar beneficial features.

FIG. **2** also shows planar surfaces **302**, **304**, **308**, and **314**, legs or sides **310** and **312**, and width **300**.

FIG. **3** shows a single two-phase ring-core coupled inductor **43**, in accord with one embodiment. Inductor **43** may be combined with other embodiments herein, for example, to serve as inductor **28** of FIG. **1**. The ring-core inductor **43** is formed from a ring magnetic core **44**. The core **44** has a passageway **45**; windings **40** and **42** are wound through passageway **45** and about the core **44**, as shown. In this embodiment, core **44** is formed as a single magnetic core; however multiple magnetic cores, such as two semi-circles, may be cooperatively combined to form a similar core structure. Other single magnetic core embodiments shown herein may also be formed by cooperatively combining multiple magnetic cores as discussed in FIG. **17**. Such a combination may align plane **44**P of magnetic core **44** in the same plane of other magnetic cores **44**, for example to facilitate mounting to a PCB. At least part of passageway **45** is free from intervening magnetic structure between windings **40**, **42**; air may for example fill the space of passageway **45** and between windings **40**, **42**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **40**, **42**, and within passageway **45**.

In one embodiment, windings **40**, **42** wind through passageway **45** and around ring magnetic core **44** such that ring magnetic core **44** and windings **40**, **42** cooperate with two phase coupling within a switching power converter. Winding **40** is oriented such dc current in winding **40** flows in a first direction within passageway **45**; winding **42** is oriented such that dc current in winding **42** flows in a second direction within passageway **45**, where the first direction is opposite to the second direction. Such a configuration avoids dc saturation of core **44**, and effectively reduces ripple current. See U.S. Pat. No. 6,362,986.

FIG. **4** shows a vertically mounted two-phase coupled inductor **54**, in accord with one embodiment. Inductor **54** may be combined and/or formed with other embodiments herein, for example, to serve as inductor **28** of FIG. **1**. The inductor **54** is formed as a rectangular-shaped magnetic core **55**. The core **55** forms a passageway **56**; windings **50** and **52** may be wound through passageway **56** and about the core **55**. In this embodiment, the inductor **54** may be vertically mounted on a plane of PCB **57** (e.g., one end of passageway **56** faces the plane of the PCB **57**) so as to minimize a "footprint", or real estate, occupied by the inductor **54** on the PCB **57**. This embodiment may improve board layout convenience. Windings **50** and **52** may connect to printed traces **59**A, **59**B on the PCB **57** for receiving current. Additionally, windings **50** and **52** may be used to mount inductor **54** to the PCB **57**, such as by flat portions **50**P, **52**P of respective windings **50**, **52**. Specifically, portions **50**P, **52**P may be soldered underneath to PCB **57**. At least part of passageway **56** is free from intervening magnetic structure between windings **50**, **52**; air may for example fill the space of passageway **56** and between windings **50**, **52**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **50**, **52**, and within passageway **56**; by way of example, the cross-sectional area of passageway **56** may be defined by the plane of dimensions **53**A (height), **53**B (depth), which is perpendicular to a line **53**C (separation distance) between windings **50**, **52**. Also shown in FIG. **4** are widths **352** and **354**, legs **356** and **358**, planar surfaces **360**, **362**, **364**, **366**, **368**, **372**, and **374**.

FIG. **4** further has advantages in that one winding **50** winds around one side of core **55**, while winding **52** winds around another side of core **55**, as shown. Such a configuration thus provides for input on one side of inductor **54** and output on the other side with convenient mating to a board layout of PCB **57**.

FIG. **5** shows a two-phase coupled inductor **60**, in accord with one embodiment. Inductor **60** may, for example, serve as inductor **28** of FIG. **1**. The inductor **60** may be formed from first and second magnetic cores **61** and **62**, respectively. The illustration of the cores **61** and **62** is exaggerated for the purpose of showing detail of inductor **60**. The two cores **61** and **62** may be "sandwiched" about the windings **64** and **63**. The dimensions E, C and A, in this embodiment, are part of the calculation that determines a leakage inductance for inductor **60**. The dimensions of D, C, and A, combined with the thickness of the first and second cores **61** and **62**, are part of the calculation that determines a magnetizing inductance of the inductor **60**. For example, assuming dimension D is much greater than E, the equations for leakage inductance and magnetizing inductance can be approximated as:

$$L_1 = \frac{\mu_0 * E * C}{2 * A} \text{ and} \tag{1}$$

$$Lm = \mu_0 * D * C / (4 * A) \tag{2}$$

where μ_0 is the permeability of free space, L_1 is leakage inductance, and L_m is magnetizing inductance. One advantage of this embodiment is apparent in the ability to vary the leakage and the magnetizing inductances by varying the dimensions of inductor **60**. For example, the leakage inductance and the magnetizing inductance can be controllably varied by varying the dimension E (e.g., the distance between the windings **64** and **63**). In one embodiment, the cores **61** and **62** may be formed as conductive prints, or traces, directly with a PCB, thereby simplifying assembly processes of circuit construction such that windings **63**, **64** are also PCB traces that couple through one or more planes of a multi-plane PCB. In one embodiment, the two-phase inductor **60** may be implemented on a PCB as two parallel thin-film magnetic cores **61** and **62**. In another embodiment, inductor **60** may form planar surfaces **63**P and **64**P of respective windings **63**, **64** to facilitate mounting of inductor **60** onto the PCB. Dimensions E, A between windings **63**, **64** may define a passageway through inductor **60**. At least part of this passageway is free from intervening magnetic structure between windings **63**, **64**; air may for example fill the space of the passageway and between windings **63**, **64**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **63**, **64**, and within the passageway; by way of example, the cross-sectional area of the passageway

may be defined by the plane of dimensions A, C, which is perpendicular to a line parallel to dimension E between windings **63**, **64**.

FIG. **6** shows a scalable, multi-phase coupled inductor **70** that may be formed from a plurality of H-shaped magnetic cores **74**, in accord with one embodiment. Inductor **70** may, for example, serve as inductor **28** of FIG. **1**. The inductor **70** may be formed by coupling "legs" **74**A of each H-shaped core **74** together. Each core **74** has one winding **72**. The windings **72** may be wound through the passageways **71** formed by legs **74**A of each core **74**. The winding of each core **74** may be wound prior to coupling the several cores together such that manufacturing of inductor **70** is simplified. By way of example, cores **74** may be made and used later; if a design requires additional phases, more of the cores **74** may be coupled together "as needed" without having to form additional windings **72**. Each core **74** may be mounted on a PCB, such as PCB **57** of FIG. **4**, and be coupled together to implement a particular design. One advantage to inductor **70** is that a plurality of cores **74** may be coupled together to make a multi-core inductor that is scalable. In one embodiment, H-shaped cores **74** cooperatively form a four-phase coupled inductor. Other embodiments may, for example, scale the number of phases of the inductor **70** by coupling more H-shaped cores **74**. For example, the coupling of another H-shaped core **74** may increase the number of phases of the inductor **70** to five. In one embodiment, the center posts **74**C about which the windings **72** are wound may be thinner (along direction D) than the legs **74**A (along direction D). Thinner center posts **74**C may reduce winding resistance and increase leakage inductance without increasing the footprint size of the coupled inductor **70**. Each of the H-shaped cores **74** has a planar surface **74**P, for example, that aligns with other H-shaped cores in the same plane and facilitates mounting of inductor **70** onto PCB **74**S. At least part of one passageway **71**, at any location along direction D within the one passageway, is free from intervening magnetic structure between windings **72**; for example air may fill the three central passageways **71** of inductor **70** and between windings **72** in those three central passageways **71**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **72**, and within passageway **71**.

FIG. **7** shows a scalable, multi-phase coupled inductor **75** formed from a plurality of U-shaped magnetic cores **78** and an equal number of I-shaped magnetic cores **79** (e.g., bars), in accord with one embodiment. Inductor **75** may, for example, serve as inductor **28** of FIG. **1**. The U-shaped cores **78** coupled with the I-shaped cores **79** may form rectangular-shaped core cells **75**A, **75**B, **75**C, and **75**D, each of which is similar to the cell of FIG. **2**, but for the winding placement. The inductor **75** may be formed by coupling each of the rectangular-shaped core cells **75**A, **75**B, **75**C, and **75**D together. The windings **76** and **77** may be wound through the passageways (labeled "APERTURE") formed by the couplings of cores **78** with cores **79** and about core elements. Similar to FIG. **6**, the windings **76** and **77** of each rectangular-shaped core cell may be made prior to coupling with other rectangular-shaped core cells **75**A, **75**B, **75**C, and **75**D such that manufacturing of inductor **75** is simplified; additional inductors **75**, may thus, be implemented "as needed" in a design. One advantage to inductor **75** is that cells **75**A, **75**B, **75**C, and **75**D—and/or other like cells—may be coupled together to make inductor **75** scalable. In the illustrated embodiment of FIG. **7**, rectangular-shaped cells **75**A, **75**B, **75**C, and **75**D cooperatively form a five-phase coupled inductor. Each of the I-shaped cores **79** has a planar surface **79**P, for example, that aligns with other I-shaped cores in the same plane and facilitates mounting of inductor **75** onto PCB **79**S. At least part of the Apertures is free from intervening magnetic structure between windings **76**, **77**; air may for example fill the space of these passageways and between windings **76**, **77**. By way of example, each Aperture is shown with a pair of windings **76**, **77** passing therethrough, with only air filling the space between the windings **76**, **77**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **76**, **77**, and within each respective Aperture.

FIG. **8** shows a scalable, multi-phase coupled inductor **80** formed from a plurality of U-shaped magnetic cores **81** (or C-shaped depending on the orientation), in accord with one embodiment. Each magnetic core **81** has two lateral members **81**L and an upright member **81**U, as shown. Inductor **80** may, for example, serve as inductor **28** of FIG. **1**. The inductor **80** may be formed by coupling lateral members **81**L of each U-shaped core **81** (except for the last core **81** in a row) together with the upright member **81**U of a succeeding U-shaped core **81**, as shown. The windings **82** and **83** may be wound through the passageways **84** formed between each pair of cores **81**. Scalability and ease of manufacturing advantages are similar to those previously mentioned. For example, winding **82** and its respective core **81** may be identical to winding **83** and its respective core **81**, forming a pair of like cells. More cells can be added to desired scalability. Each of the U-shaped cores **81** has a planar surface **81**P, for example, that aligns with other U-shaped cores **81** in the same plane and facilitates mounting of inductor **80** onto PCB **81**S. At least part of one passageway **84** is free from intervening magnetic structure between windings **82**, **83**; air may for example fill the space of this passageway **84** and between windings **82**, **83**. By way of example, three passageways **84** are shown each with a pair of windings **82**, **83** passing therethrough, with only air filling the space between the windings **82**, **83**. One winding **82** is at the end of inductor **80** and does not pass through such a passageway **84**; and another winding **83** is at another end of inductor **80** and does not pass through such a passageway **84**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **82**, **83**, and within passageway **84**.

FIG. **9** shows a multi-phase coupled inductor **85** formed from a comb-shaped magnetic core **86** and an I-shaped (e.g., a bar) magnetic core **87**, in accord with one embodiment. Inductor **85** may, for example, serve as inductor **28** of FIG. **1**. The inductor **85** may be formed by coupling a planar surface **86**P of "teeth" **86**A of the comb-shaped core **86** to a planar surface **87**P of the I-shaped core **87** in substantially the same plane. The windings **88** and **89** may be wound through the passageways **86**B formed by adjacent teeth **86**A of comb-shaped core **86** as coupled with I-shaped core **87**. The windings **88** and **89** may be wound about the teeth **86**A of the comb-shaped core **86**. FIG. **9** also shows end passageways **200**, planar surfaces **202**, **204**, **206**, **208**, **210**, **212**, **214**, and **224**, height **216**, depth **218**, and widths **220** and **222**. This embodiment may also be scalable by coupling inductor **85** with other inductor structures shown herein. For example, the U-shaped magnetic cores **81** of FIG. **8** may be coupled to inductor **85** to form a multi-phase inductor, or a N+1 phase inductor. The I-shaped core **87** has a planar surface **87**P, for example, that facilitates mounting of inductor **85** onto PCB **87**S. At least part of one passageway **86**B is free from intervening magnetic structure between windings **88**, **89**; air may for example fill the space of this passageway **86**B and between windings **88**, **89**. By way of example, three passageways **86**B are shown each with a pair of windings **88**, **89**

passing therethrough, with only air filling the space between the windings **88**, **89**. One winding **88** is at the end of inductor **85** and does not pass through such a passageway **86**B; and another winding **89** is at another end of inductor **85** and does not pass through such a passageway **86**B. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **88**, **89**, and within passageway **86**B.

In one embodiment, windings **88**, **89** wind around teeth **86**A of core **86**, rather than around I-shaped core **87** or the non-teeth portion of core **86**.

FIG. **10** shows a scalable, multi-phase coupled inductor **90** that may be formed from a comb-shaped magnetic core **92** and an I-shaped (e.g., a bar) magnetic core **93**, in accord with one embodiment. Inductor **90** may, for example, serve as inductor **28** of FIG. **1**. The inductor **90** may be formed by coupling "teeth" **92**A of the comb-shaped core **92** to the I-shaped core **93**, similar to FIG. **8**. The inductor **90** may be scaled to include more phases by the addition of the one more core cells to form a scalable structure. In one embodiment, H-shaped cores **91** (such as those shown in FIG. **6** as H-shaped magnetic cores **74**), may be coupled to cores **92** and **93**, as shown. The windings **94** and **95** may be wound through the passageways **90**A formed by the teeth **92**A as coupled with I-shaped core **93**. The windings **94** and **95** may be wound about the teeth **92**A of core **92** and the "bars" **91**A of H-shaped cores **91**. Scalability and ease of manufacturing advantages are similar to those previously mentioned. Those skilled in the art should appreciate that other shapes, such as the U-shaped cores and rectangular shaped cores, may be formed similarly to cores **92** and **93**. Each of the I-shaped core **92** and the H-shaped cores **91** has a respective planar surface **92**P and **91**P, for example, that aligns in the same plane and facilitates mounting of inductor **90** onto PCB **90**S. At least part of one passageway **90**A is free from intervening magnetic structure between windings **94**, **95**; air may for example fill the space of this passageway **90**A and between windings **94**, **95**. By way of example, five passageways **90**A are shown each with a pair of windings **94**, **95** passing therethrough, with only air filling the space between the windings **94**, **95**. One winding **94** is at the end of inductor **90** and does not pass through such a passageway **90**A; and another winding **95** is at another end of inductor **90** and does not pass through such a passageway **90**A. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **94**, **95**, and within passageway **90**A.

FIGS. **11-13** show staple magnetic cores **102** that may serve to implement a scalable multi-phase coupled inductor **100**. Inductor **100** may, for example, serve as inductor **28** of FIG. **1**. The staple magnetic cores **102** are, for example, U-shaped and may function similar to a "staple". The staple magnetic cores **102** may connect, or staple, through PCB **101** to bus bars **103** to form a plurality of magnetic core cells. For example, the two bus bars **103** may be affixed to one side of PCB **101** such that the staple magnetic cores **102** traverse through the PCB **101** from the opposite side of the PCB (e.g., via apertures **101**H) to physically couple to the bus bars **103**. One staple magnetic core may implement a single phase for the inductor **100**; thus the inductor **100** may be scalable by adding more of staple magnetic cores **102** and windings **104**, **105**. For example, a two-phase coupled inductor would have two staple magnetic cores **102** coupled to bus bars **103** with each core having a winding, such as windings **104**, **105**; the number of phases are thus equal to the number of staple magnetic cores **102** and windings **104**, **105**. By way of example, inductor **100**, FIG. **11**, shows a 3-phase inductor.

Bus bars **103** may have center axes **402** and staple magnetic cores **102** may have center axes **404**.

Advantages of this embodiment provide a PCB structure that may be designed in layout. As such, PCB real estate determinations may be made with fewer restrictions, as the inductor **100** becomes part of the PCB design. Other advantages of the embodiment are apparent in FIG. **13**. There, it can be seen that the staples **102** may connect to PCB **101** at angles to each PCB trace (i.e., windings **104** and **105**) so as to not incur added resistance while at the same time improving adjustability of leakage inductance. For example, extreme angles, such as 90 degrees, may increase the overall length of a PCB trace, which in turn increases resistance due to greater current travel. Further advantages of this embodiment include the reduction or avoidance of solder joints, which can significantly diminish high current. Additionally, the embodiment may incur fewer or no additional winding costs as the windings are part of the PCB; this may improve dimensional control so as to provide consistent characteristics such as AC resistance and leakage inductance.

Similar to coupled inductor **100**, FIG. **14** shows bar magnetic cores **152**, **153** that serve to implement a scalable coupled inductor **150**. Inductor **150** may, for example, serve as inductor **28** of FIG. **1**. The bar magnetic cores **152**, **153** are, for example, respectively mounted to opposing sides **156**, **157** of PCB **151**. Each of the bar magnetic cores **152**, **153** has, for example, a respective planar surface **152**P, **153**P that facilitates mounting of the bar magnetic cores to PCB **151**. The bar magnetic cores **152**, **153**, in this embodiment, do not physically connect to each other but rather affix to the sides of **156**, **157** such that coupling of the inductor **150** is weaker. The coupling of the inductor **150** may, thus, be determinant upon the thickness of the PCB **151**; this thickness forms a gap between cores **152** and **153**. One example of a PCB that would be useful in such an implementation is a thin polyimide PCB. One bar magnetic core **152** or **153** may implement a single phase for the inductor **150**; and inductor **150** may be scalable by adding additional bar magnetic cores **152** or **153**. For example, a two-phase coupled inductor has two bar magnetic cores **152** coupled to two bus bars **153**, each core having a winding **154** or **155** respectively. The number of phases are therefore equal to the number of bar magnetic cores **152**, **153** and windings **154**, **155**. One advantage of the embodiment of FIG. **14** is that no through-holes are required in PCB **151**. The gap between cores **152** and **153** slightly reduces coupling so as to make the DC-to-DC converter system using coupled inductor **150** more tolerant to DC current mismatch. Another advantage is that all the cores **152**, **153** are simple, inexpensive I-shaped magnetic bars. Cores **152** may have center axes **408**, and cores **153** may have center axes **406**.

FIGS. **15-16** each show a multi-phase coupled inductor (e.g., **110** and **120**, respectively) with through-board integration, in accord with other embodiments. FIG. **15** shows a coupled inductor **110** that may be formed from a comb-shaped core **111** coupled to an I-shaped core **112** (e.g., a bar), similar to that shown in FIG. **9**. In this embodiment, the cores **111** and **112** may be coupled through PCB **113** and are integrated with PCB **113**. The windings **114**, **115** may be formed in PCB **113** and/or as printed circuit traces on PCB **113**, or as wires connected thereto.

In FIG. **15**, comb-shaped core **111** and I-shaped core **112** form a series of passageways **117** within coupled inductor **110**. At least part of one passageway **117** is free from intervening structure between windings **114**, **115**; air may for example fill the space of this passageway **117** and between windings **114**, **115**. By way of example, three passageways **117** are shown each with a pair of windings **114**, **115** passing

therethrough, with non-magnetic structure of PCB **113** filling some or all of the space between the windings **114**, **115**. One winding **114** is at the end of inductor **110** and does not pass through such a passageway **117**; and another winding **115** is at another end of inductor **110** and does not pass through such a passageway **117**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **114**, **115**, and within passageway **117**.

FIG. **16** shows another through-board integration in a coupled inductor **120**. In this embodiment, magnetic cores **121** and **122** may be coupled together by "sandwiching" the cores **121**, **122** about PCB **123**. The connections to the cores **121**, **122** may be implemented via holes **126** in the PCB **123**. The holes **126** may be filled with a ferromagnetic powder and/or bar that couples the two cores together, when sandwiched with the PCB **123**. Similarly, the windings **124**, **125** may be formed in PCB **123** and/or as printed circuit traces on PCB **123**, or as wires connected thereto. Inductors **110** and **120** may, for example, serve as inductor **28** of FIG. **1**. In this embodiment, the windings **114** and **115** are illustrated as PCB traces located within a center, or interior, plane of the PCB **123**. Those skilled in the art should readily appreciate that the windings **114** and **115** may be embedded into any layer of the PCB and/or in multiple layers of the PCB, such as exterior and/or interior layers of the PCB.

In FIG. **16**, cores **121** and **122** and ferromagnetic-filled holes **126** form a series of passageways **118** within coupled inductor **120**. At least part of one passageway **118** is free from intervening structure between windings **124**, **125**; air may for example fill the space of this passageway **118** and between windings **124**, **125**. By way of example, three passageways **118** are shown each with a pair of windings **124**, **125** passing therethrough, with non-magnetic structure of PCB **123** filling some or all of the space between the windings **124**, **125**. One winding **124** is at the end of inductor **120** and does not pass through such a passageway **118**; and another winding **125** is at another end of inductor **120** and does not pass through such a passageway **118**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **124**, **125**, and within passageway **118**.

FIG. **17** shows a multi-phase scalable coupled ring-core inductor **130**, in accord with one embodiment. The inductor **130** may be formed from multiple ring magnetic cores **131**A, **131**B, and **131**C. In this embodiment, cores **131**A, **131**B, and **131**C may be coupled to one another. The ring magnetic cores **131**A, **131**B, and **131**C may have respective planar surfaces **131**AP, **131**BP, and **131**CP, for example, that align in the same plane, to facilitate mounting with electronics such as a PCB. Each core may have an passageway **135** through which windings **132**, **133**, and **134** may be wound. As one example, cores **131**A and **131**B may be coupled to one another as winding **133** may be wound through the passageways and about the cores. Similarly, cores **131**B and **131**C may be coupled to one another as winding **132** may be wound through the passageways **135** of those two cores. Cores **131**C and **131**A may be coupled to one another as winding **134** is wound through the passageways of those two cores. In another embodiment, the multiple ring magnetic cores **131**A, **131**B, and **131**C may be coupled together by windings such that inductor **130** appears as a string or a chain. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between the windings within each respective passageway **135**.

While some inductor embodiments include two-phase coupling, such as those shown in FIGS. **2-5**, it is not intended that inductor coupling should be limited to two-phases. For example, a coupled inductor with two windings would function as a two-phase coupled inductor with good coupling, but coupling additional inductors together may advantageously increase the number of phases as a matter of design choice. Integration of multiple inductors that results in increased phases may achieve current ripple reduction of a power unit coupled thereto; examples of such are shown in FIGS. **6-8**, **10**, and **17**. Coupling two or more two-phase inductor structures together to create a scalable N-phase coupled inductor may achieve an increased number of phases of an inductor. The windings of such an N-phase coupled inductor may be wound through the passageways and about the core such as those shown in FIGS. **6-8**, **10**, and **17**.

Since certain changes may be made in the above methods and systems without departing from the scope hereof, one intention is that all matter contained in the above description or shown in the accompanying drawings be interpreted as illustrative and not in a limiting sense. By way of example, those skilled in the art should appreciate that items as shown in the embodiments may be constructed, connected, arranged, and/or combined in other formats without departing from the scope of the invention. Another intention includes an understanding that the following claims are to cover all generic and specific features of the invention described herein, and all statements of the scope of the invention which, as a matter of language, might be said to fall there between.

We claim:

1. A two phase coupled inductor for magnetically coupling first and second phases of a power converter, comprising:

a magnetic core forming a passageway having depth and height, the depth being greater than the height;

a first winding providing electrical interface for the first phase; and

a second winding providing electrical interface for the second phase,

the first and second windings being wound at least partially around a common leg of the magnetic core and through the passageway, the first and second windings extending through the magnetic core only via the passageway,

the second winding being separated from the first winding by a linear separation distance throughout the passageway, the separation distance being along an axis perpendicular to an axis of the height of the passageway and perpendicular to an axis of the depth of the passageway, the separation distance being greater than the height of the passageway, and

the depth and the height of the passageway defining a cross sectional area of the passageway, the cross sectional area of the passageway between the first and second windings being at least partially free from intervening magnetic structure.

2. Two phase coupled inductor of claim **1**, each winding having two ends, each end forming a tab having rectangular cross section.

3. Two phase coupled inductor of claim **2**, at least one of the tabs being solderable to a printed circuit board.

4. Two phase coupled inductor of claim **2**, at least one of the tabs being folded underneath the magnetic core.

5. Two phase coupled inductor of claim **1**, at least one of the first winding and the second winding comprising a single turn.

6. Two phase coupled inductor of claim **1**, the magnetic core having width, and a ratio of the separation distance to the width being at least about 0.2.

7. Two phase coupled inductor of claim **1**, wherein

a ratio of magnetizing inductance of the inductor to leakage inductance of either winding is greater than or equal to about 3.

8. Two phase coupled inductor of claim **1**, further comprising a non-magnetic material having thickness forming a gap in the magnetic core, the gap being operable to reduce likelihood of saturation of the two phase coupled inductor if the two phase coupled inductor is used in a switching power converter, the thickness of the non-magnetic material being less than the height of the passageway.

9. Two phase coupled inductor of claim **1**, the magnetic core further comprising a center leg extending into the passageway.

10. Two phase coupled inductor of claim **1**, wherein each of the first winding and the second winding comprises a single turn.

11. Two phase coupled inductor of claim **1**, wherein the passageway has a rectangular shape.

12. A coupled inductor, comprising:

a magnetic core having a bottom side, a first side, and a second side opposite of the first side, the magnetic core forming a passageway extending from the first side to the second side, the passageway having depth and height defining a cross-sectional area of the passageway, the magnetic core including an outer leg extending from the first side to the second side and partially defining the passageway; and

a first and a second winding having a same number of turns, the first and second windings wound at least partially around the outer leg and through the passageway, the first and second windings separated by a linear separation distance throughout the passageway, the separation distance being along an axis perpendicular to an axis of the height of the passageway and perpendicular to an axis of the depth of the passageway, the separation distance being greater than the height of the passageway, the cross-sectional area of the passageway between the windings being at least 50% free of magnetic material, each winding having a respective first end and a respective second end extending to the bottom side of the magnetic core for soldering to a printed circuit board.

13. Coupled inductor of claim **12**, the magnetic core having a rectangular shape, and the first and second sides being orthogonal to the bottom side.

14. Coupled inductor of claim **12**, the magnetic core forming a single passageway.

15. Coupled inductor of claim **12**, the passageway depth being greater than the passageway height.

16. A two phase DC-to-DC converter, comprising:

a two phase coupled inductor, including:

a magnetic core forming a passageway, the passageway having depth and height defining a cross-sectional area of the passageway, and

a first and a second winding having a same number of turns wound at least partially around a common leg of the magnetic core and through the passageway, the first and second windings separated by a linear separation distance throughout the passageway the separation distance being along an axis perpendicular to an axis of the height of the passageway and perpendicular to an axis of the depth of the passageway, each winding having a respective first end and a respective second end, the second ends of the first and second windings being electrically connected to a common load, the cross-sectional area of the passageway between the windings being at least 50% free of magnetic material;

a first switch electrically connected between a power source and the first end of the first winding; and

a second switch electrically connected between the power source and the first end of the second winding;

wherein the first and second switches independently and sequentially switch the first end of their respective winding to an input signal of the power source to regulate an output signal at the load.

17. DC-to-DC converter of claim **16**, the DC-to-DC converter configured and arranged such that:

direct current flowing through the first winding from the first switch to the load generates a magnetic flux flowing in a first direction in the magnetic core; and

direct current flowing through the second winding from the second switch to the load generates a magnetic flux flowing in a second direction in the magnetic core, the second direction being opposite of the first direction.

18. DC-to-DC converter of claim **17**, the separation distance being greater than the height of the passageway.

19. DC-to-DC converter of claim **17**, a switching cycle of the first switch being about 180 degrees out of phase with a switching cycle of the second switch.

20. DC-to-DC converter of claim **17**, the first and second windings being single turn windings.

21. DC-to-DC converter of claim **17**, the magnetic core forming a single passageway.

22. DC-to-DC converter of claim **17**, the passageway having a rectangular shape.

23. A two phase coupled inductor for magnetically coupling first and second phases of a power converter, comprising:

a magnetic core forming a passageway at least partially defined by first, second, third, and fourth planar surfaces of the magnetic core, the first planar surface being opposite of the second planar surface, the third planar surface being opposite of the fourth planar surface;

a first winding providing electrical interface for the first phase, the first winding wound at least partly about the magnetic core and passing through the passageway along the first planar surface and contacting the third planar surface; and

a second winding providing electrical interface for the second phase, the second winding wound at least partly about the magnetic core and passing through the passageway along the first planar surface and contacting the fourth planar surface,

the passageway having depth and height, the depth being greater than the height,

the first and second windings extending through the magnetic core only via the passageway, and

the first and second windings being separated by a linear separation distance throughout the passageway, the separation distance being along an axis perpendicular to an axis of the height of the passageway and perpendicular to an axis of the depth of the passageway, the separation distance being greater than the height of the passageway.

24. Two phase coupled inductor of claim **23**, the depth and height of the passageway defining a cross sectional area of the passageway, and the cross sectional area of the passageway between the first and second windings being at least partially free from intervening magnetic structure.

25. Two phase coupled inductor of claim **23**, the magnetic core further comprising:

a first magnetic core having the second planar surface; and
a second magnetic core coupled to the first magnetic core, the second magnetic core having the first planar surface;
the first magnetic core and the second magnetic core cooperatively forming the passageway.

26. Two phase coupled inductor of claim **23**, at least one of the first winding and the second winding comprising rectangular cross section.

27. Two phase coupled inductor of claim **23**, each winding having two ends, and each end forming a solderable tab for connection to a printed circuit board.

28. Two phase coupled inductor of claim **23**, the power converter comprising a two phase DC-to-DC converter that produces an output voltage from an input voltage, the DC-to-DC converter switching a first voltage across the first winding at about 180 degrees out of phase with a second voltage across the second winding to regulate a magnitude of the output voltage, and the first and second voltages being formed from one or a combination of the input and output voltages.

29. Two phase coupled inductor of claim **28**, wherein the DC-to-DC converter is constructed and arranged such that a first magnetic flux generated by the first winding and a second magnetic flux generated by the second winding flow in a common direction within the magnetic core during at least one sub period of an operating period of the two phase DC-to-DC converter.

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